prion-contaminated dura graft transplantation with two to three times prolonged incubation period compared with those after the intracerebral inoculation, whereas sham-operated or PBS-treated littermates remained healthy for over 300 days after the operation.

Starting at 60 days after the transplantation, Western blot analysis detected discrete mouse PrP^{Sc} signals even from asymptomatic Tg(MoPrP-A)B4053 brains receiving the prion-contaminated dura graft transplantation in a time-dependent manner (Fig. 1B). Concomitant with spongiform degeneration by light microscopy (Fig. 2A), immunohistochemical analyses further disclosed the considerable PrP^{Sc} accumulations in the transplanted cortical areas as well as in the ipsilateral thalamus at 120 days after the transplantation (Fig. 2B), which might support the assumption that the spread of prions occurs axonally after intraocular injection [11].

As a therapeutic and prophylactic approach, we next performed 7-day intracerebroventricular administration of rPrP-Q218K via an indwelling catheter connected to implanted osmotic pump at either 30 or 60 days after prion-contaminated dura graft transplantation. The control group, Tg(MoPrP-A)B4053 treated with PBS alone, died at 117 days after transplantation. To our surprise, the median incubation period of Tg(MoPrP-A)B4053 was markedly prolonged for as long as 131 days even after a long latency period for as long as 30 days by starting the rPrP-Q218K injection (Fig. 3), which was statistically significant compared with that of the control group ($p = 0.016$, log-rank test). After a very long latency period of 60 days by starting the rPrP-Q218K treatment, however, the median incubation period of mice was 113 days, which was not statistically significant (Fig. 3).

For potential iCJD patients who received dura graft transplantations in the past, an effective and efficient prophylactic method has been anticipated. Toward the exploration of such prophylactics, development of an animal model of iCJD after dura graft transplantation is apparently fundamental and crucial.

The intracerebral inoculation of tissue homogenates into suitable recipients is the most effective method for transmission of prion diseases and frequently allows the species barrier to be circumvented. Alternatively, intraperitoneal injection has been used for studies of extra-central nervous system involvement. However, these procedures are unsuitable for investigation of the iCJD after dura graft transplantation because the mode of prion propagation is markedly different. For that reason, we have established for the first time the mouse model of iCJD after artificial dura graft transplantation, in which prion transmission occurs via cortico-dural interface; it has two to three times longer incubation period than that after intracerebral inoculation.

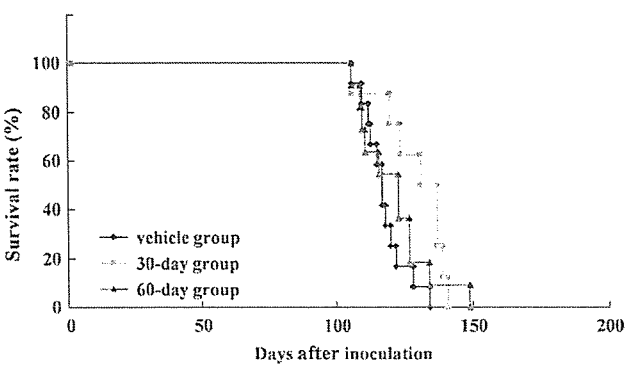

Fig. 3. Kaplan–Meyer survival analysis of highly prion-susceptible Tg(MoPrP-A)B4053 with the dominant negative rPrP-Q218K treatment. The Tg(MoPrP-A)B4053 with the dominant negative rPrP-Q218K treatment started at 30 days after prion-contaminated dura graft transplantation survived significantly longer ($p = 0.016$) than those of the control group.

So far, no effective prophylactic or therapeutic method is available in prion-infected mice during the asymptomatic preclinical phase [7,21] because it is preliminary to consider gene therapeutics, e.g. an ex vivo gene transfer approach [8,14,15]. Furthermore, a recent clinical trial of Aβ vaccination targeting Alzheimer's disease was halted because of the serious neurological complications of autoimmune reactions developing in some patients [10,18].

Human PrP polymorphism at codon 219 has been reported in the Japanese population [16]. Among Japanese, 12% carry the lysine allele, but the lysine allele in place of glutamine has not been found in 85 autopsied sporadic CJD cases, suggesting that the lysine substitution at human codon 219 (E219K), which corresponds to mouse Q218K, might act as a dominant negative form in prion propagation [16,28]. As mentioned, we have reported that the administration of dominant negative rPrP-Q218K sufficiently inhibits PrP^{Sc} formation in ScN2a cells in vitro [15]. For those reasons, further investigation of its therapeutic equivalence must be done in an in vivo setting.

Intrathecal injection is an efficient option for delivery of therapeutic reagents into the brain because the blood–brain barrier (BBB) is often the rate-limiting factor in determining permeation of these reagents in vivo [1,9]. In a preclinical SOD1(G93A) rat model of amyotrophic lateral sclerosis, for example, intracerebroventricular delivery of recombinant vascular endothelial growth factor delays onset of paralysis by 17 days; it also improves motor performance and prolongs survival by 22 days [30]. In humans, clinical applications with continuous intrathecal administration of various therapeutic reagents including bacrofen [17], anti-cancer drugs [20], analgesics [26], and neuroleptics [27] have been used widely and have been found to be effective. These observations further support inferences from our current data in the mouse model of iCJD.

Although limited, intracerebroventricular administration of rPrP-Q218K delayed the onset of prion disease with a longer survival period in the mouse model of iCJD in vivo. A salient advantage is the fact that homogeneous and high-quality rPrP-Q218K can be readily prepared from large-scale fermentation of *E. coli* in large quantities. At the same time, it is also important to introduce wild-type or other mutant rPrPs into the current experimental setting, since the rPrPs itself may interfere with the prion replication in vivo even without the Q218K substitution. Whether wild-type rPrP, other mutant rPrPs, or the combination of rPrP-Q218K with anti-prion compounds might extend the survival period in an in vivo setting remains to be further investigated.

Acknowledgement

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Short communication

Gene silencing analyses against *amyloid precursor protein* (*APP*) gene family by RNA interference

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Abstract

Amyloid precursor protein (*APP*) and *amyloid precursor-like proteins 1* and *2* (*APLP1* and *APLP2*) are members of a large gene family. Although APP is known to be the source of the β-amyloid peptides involved in the development of Alzheimer's disease, the normal functions of APP, APLP1 and APLP2 in cells are poorly understood. In this study, we carried out gene silencing analysis by means of RNA interference with synthetic small interfering RNA duplexes targeting the *App*, *Aplp1* and *Aplp2* genes in Neuro2a (N2a) cells, a mouse neuroblastoma cell line. The results demonstrated that cell viability and neurite outgrowth of N2a cells undergoing knockdown of *Aplp1* were significantly reduced, compared with N2a cells undergoing knockdown of either *App* or *Aplp2*.

Keywords: RNAi; App; Aplp1; Aplp2; Neuro2a cell; Neurite outgrowth; Viability

1. Introduction

Amyloid precursor protein (APP) is a membrane-spanning glycoprotein expressed in various tissues, including the brain, and is the source of β-amyloid peptides (Aβ), which are a key factor in the development of Alzheimer's disease (AD); extracellular deposition of Aβ resulting in the formation of 'senile plaques' often occurring in the brains of AD patients (Turner et al., 2003). In mammals, *amyloid precursor-like protein 1* and *2* (*APLP1* and *APLP2*) genes, which lack the Aβ region, have also been identified (Wasco et al., 1992; Wasco et al., 1993a,b), thus suggesting that *APP*, *APLP1* and *APLP2* are members of a large gene family. The expression profiles of *APP* and *APLP2* are similar, whereas expression of *APLP1* appears to be restricted to the nervous system (Lorent et al., 1995; Slunt et al., 1994). Translated APP, APLP1 and APLP2 polypeptides appear to undergo proteolytic processing by α-, β- and γ-secretase (Eggert et al., 2004; Gu et al., 2001; Li and Sudhof, 2004; Scheinfeld et al., 2002); but, the normal function of the resultant APP, APLP1 and APLP2 in cells remains largely unknown.

In this study, we carried out gene silencing analysis against the *App*, *Aplp1* and *Aplp2* genes by means of RNA interference (RNAi) in Neuro2a (N2a) cells, a mouse neuroblastoma cell line, and investigated the influence of knockdown of these genes.

2. Materials and methods

2.1. Cell culture

Neuro2a cells, a mouse neuroblastoma cell line, were grown at 37 °C in DMEM (Wako) supplemented with 10% fetal bovine serum (Sigma), 100 U/ml penicillin (Invitrogen) and 100 μg/ml streptomycin (Invitrogen) in a 5% CO_2-humidified chamber.

2.2. Small interfering RNA duplexes

Small interfering RNA (siRNA) duplexes against mouse *App*, *Aplp1*, and *Aplp2* genes were purchased from Ambion. The siRNA ID numbers (Ambion)

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were as follows: siApp-1 [60001], siApp-2 [60093], siAplp1-1 [159681], siAplp1-2 [159682], siAplp2-1 [160719], siAplp2-2 [160720]. Non-silencing siRNA duplexes were used as negative control (Qiagen).

2.3. Transfection of siRNA duplexes

The day before transfection, cells were trypsinized, diluted with fresh medium lacking antibiotics, and seeded into 24-well culture plates (1×10^4 cells/well). Transfection of siRNA duplexes was carried out using jetSI (Polyplus transfection) according to the manufacturer's instructions, with minor modifications. Before transfection, the culture medium was replaced with 0.4 ml OPTI-MEM I (Invitrogen), and to each well, 40 nM siRNA duplex was applied. Cells were incubated for 4 h at 37 °C. After the 4 h incubation, 1 ml of the fresh culture medium without antibiotics was added, and further incubation was carried out.

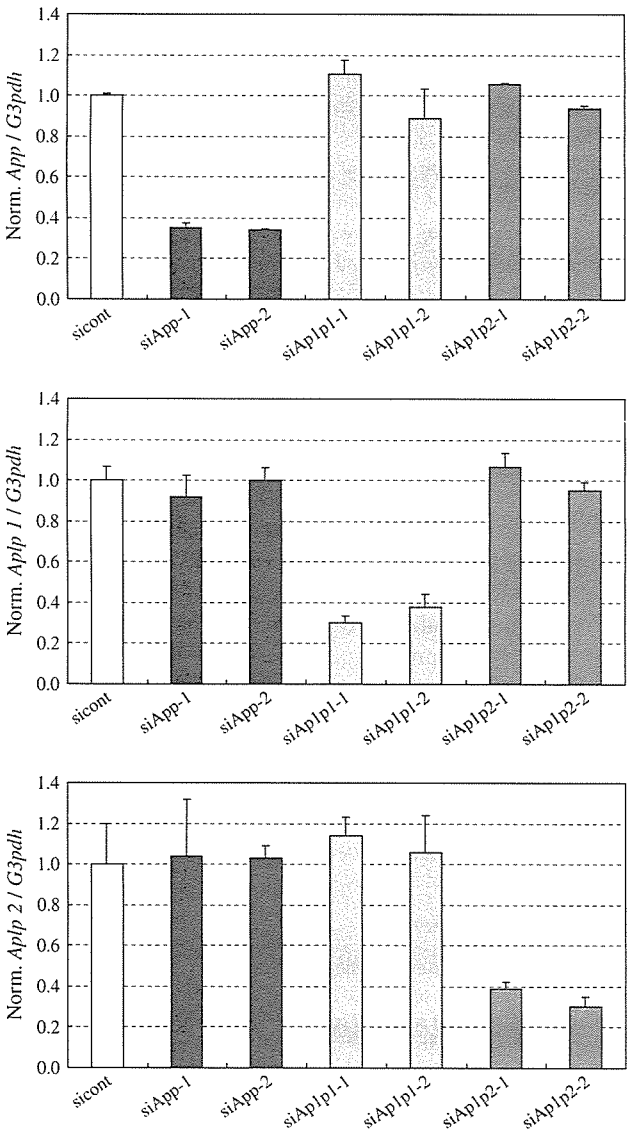

Fig. 1. Expression profiles of *App*, *Aplp1* and *Aplp2* in N2a cells. Indicated siRNA duplexes were transfected into N2a cells. Twelve hours after transfection, total RNA was extracted from the cells, and was subjected to RT-(real-time) PCR. Expression levels of *App*, *Aplp1*, or *Aplp2* were normalized against those of *G3pdh*, and the ratios of expression levels were normalized against the ratio obtained in the presence of the siControl duplex. Data are means of at least three independent determinations. Error bars represent standard deviations.

2.4. Reverse transcription-(real-time) polymerase chain reaction

In order to examine the expression levels of the genes, total RNA was extracted from cells and was subjected to reverse transcription-(real-time) polymerase chain reaction [RT-(real-time) PCR], as described previously (Hohjoh, 2004; Ohnishi et al., 2006; Sago et al., 2004). Real-time PCR was carried out using the ABI PRISM 7300 sequence detection system (Applied Biosystems) with a TaqMan Universal PCR Master Mix together with Assays-on-Demand Gene Expression products (Applied Biosystems) according to the manufacturer's instructions. The Assays-on-Demand Gene Expression products used (Assay ID number) were as follows: *App*; Mm00431827_m1, Aplp1; Mm00545893_m1, Aplp2; Mm00507819_m1.

2.5. Western blotting

Cell lysate and culture media were examined by Western blotting as described previously (Ohnishi et al., 2006). Equal amounts of proteins were separated by SDS-PAGE and electrophoretically blotted onto PVDF membranes (Millipore). Membranes were blocked with 5% non-fat milk in PBS containing 0.05% Tween-20 and incubated with anti-APP mouse monoclonal (3E9) antibody (MBL), anti-APLP1 rabbit polyclonal antibody (Calbiochem) and anti-α-tubulin (Sigma) antibody followed by washing in PBS and further incubation with horseradish peroxidase-conjugated anti-mouse IgG (Jackson ImmunoResearch Labs) or biotinylated anti-rabbit IgG together with avidin–biotinylated horseradish peroxidase complexes (Vectastain). Antigen–antibody complexes were visualized using ECL chemiluminescent reagent (Amersham).

2.6. Cell viability assay

Cell viability was investigated using 3-(4,5-dimethylthiazol-2-yl)-5(3-carboxymethonyphenol)-2-(4-sulfophenyl)-2*H*-tetrazolium (MTS) assay using a CellTiter 96 aqueous non-radioactive cell proliferation assay kit (Promega) according to the manufacturer's instructions.

3. Results and discussion

Because the *App*, *Aplp1* and *Aplp2* genes are members of the same gene family, we first assessed whether sequence-specific

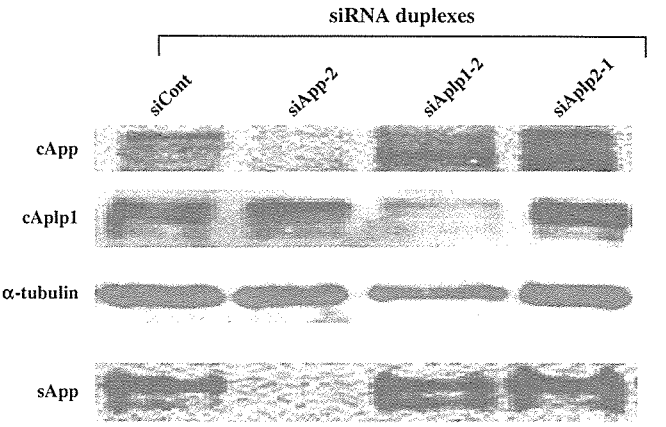

Fig. 2. Western blot analysis of App and Aplp1. Transfection of indicated siRNA duplexes into N2a cells was carried out as described for Fig. 1. Twenty-four hours after transfection, culture medium was replaced with DMEM without serum, and further 24 h culture was carried out. Cell lysate and culture media were prepared from transfected cells, and expressed App and Aplp1 in cells (cellular App and Aplp1: cApp and cAplp1) and App in culture media (secreted App: sApp) were examined by Western blotting. Expression of α-tubulin (control) was also examined. As for Aplp2, we could not obtain antibody against it in this study.

gene silencing (RNAi) was induced by siRNA duplexes. Twelve hours after transfection with the siRNA duplexes targeting *App*, *Aplp1* and *Aplp2*, the expression levels of the target genes were examined by means of RT-(real-time) PCR and Western blotting. As shown in Figs. 1 and 2, the results indicate that used siRNA duplexes were able to inhibit the expression of their own target genes without suppressing the expression of the other two genes, thus suggesting that specific

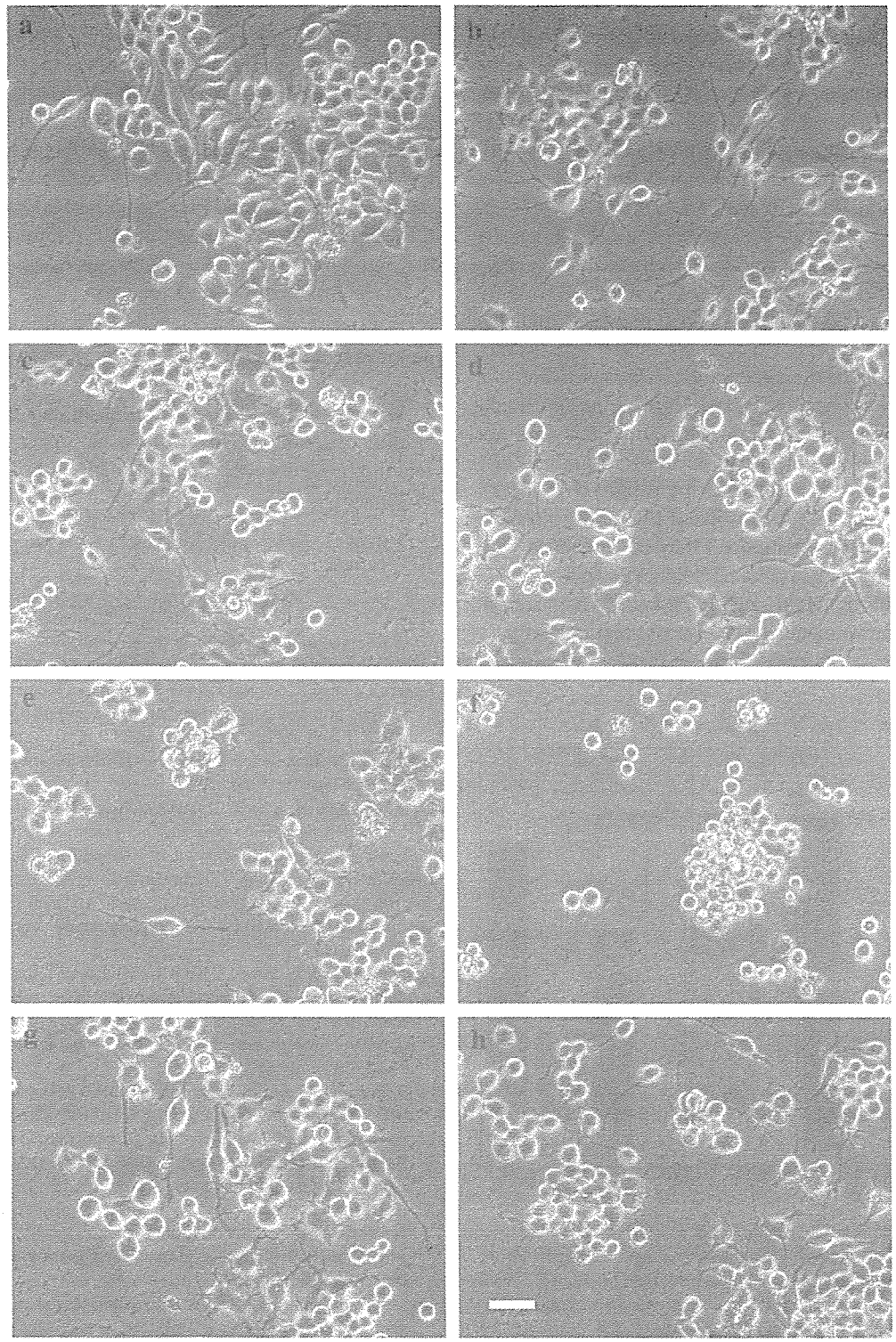

Fig. 3. Morphological differentiation of N2a cells with knockdown of *App*, *Aplp1* and *Aplp2*. Transfection of siRNA duplexes into N2a cells was carried out as described for Fig. 1. Twenty-four hours after transfection, culture medium was replaced with DMEM without serum, and further 24 h culture was carried out as described for Fig. 2. Transfected siRNA duplexes were as follows: (a) no siRNA (jetSI reagent alone); (b) siControl; (c) siApp-1; (d) siApp-2; (e) siAplp1-1; (f) siAplp1-2; (g) siAplp2-1; (h) siAplp2-2. Scale bar indicates 50 μm.

inhibition of target gene expression was induced by the siRNA duplexes.

Because N2a cells are differentiated by serum deprivation [the resultant cells exhibit differentiated morphology with long neuritic processes (Fig. 3a)] (Diaz-Nido et al., 1988), we investigated the morphological differentiation of N2a cells with knockdown of *App*, *Aplp1* and *Aplp2* under serum deprivation. Fig. 3 shows photographs of N2a cells treated with siRNA duplexes after 24 h culture in the absence of serum. Neurite outgrowth was examined based on cell body diameter (approximately 15 μm) and cells with extended neurites longer than two cell body diameters were judged to be differentiated. As shown in the figure, moderate levels of neurite outgrowth were observed in N2a cells undergoing gene silencing of *App* and *Aplp2*; in contrast, very little neurite outgrowth was seen in N2a cells with knockdown of *Aplp1*. In addition, based on the observation of transfected cells, it appears that knockdown of the *App* gene family also influences cell viability. To further confirm this observation, we examined cell viability by means of MTS assay. As shown in Fig. 4, the results indicate that: (i) N2a cells with knockdown of *Aplp1* exhibit significantly reduced viability under the present culture conditions, in both the presence and absence of serum; (ii) knockdown of *App* apparently decreases cell viability under serum deprivation, but does not significantly affect viability in the presence of serum; and (iii) knockdown of *Aplp2* in N2a cells has little influence on cell viability. Taken together with the results of Fig. 3, it is possible that the inhibition of neurite outgrowth may be associated with decreased cell viability in N2a cells with knockdown of *Aplp1*.

Previous studies of *App*, *Aplp1* and *Aplp2* knockout mice have suggested that *App* family members possess essential, but partially redundant, functions, and that they play important roles in normal brain development and early postnatal survival (Heber et al., 2000; Herms et al., 2004; von Koch et al., 1997). Of the *App* family members, *Aplp2* may have a key function, as $Aplp2^{-/-}App^{-/-}$ and $Aplp2^{-/-}Aplp1^{-/-}$ double knockout is postnatally lethal, while $App^{-/-}Aplp1^{-/-}$ double knockout mice are viable. However, $Aplp2^{-/-}$ single knockout mice appeared to be normal (von Koch et al., 1997), whereas $Aplp1^{-/-}$ single knockout mice exhibited postnatal growth deficit (Heber et al., 2000).

Based on the present observations, *Aplp1* rather than *Aplp2* appears to play an important role in Neuro2a cells. Because *Aplp1* is specifically expressed in the nervous system (Lorent et al., 1995), it is possible that *Aplp1* plays an essential role in the survival and differentiation of neuronal cells (at least N2a cells). The present and previous observations also suggest that different cells (tissues) may require different contributions by the *App* gene family. To further evaluate these possibilities, more extensive studies are required.

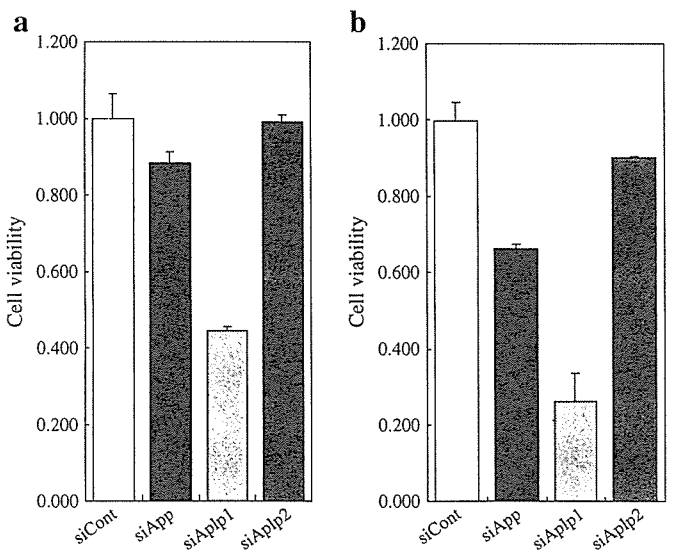

Fig. 4. Cell viability of N2a cells undergoing gene silencing of *App*, *Aplp1* and *Aplp2*. Transfection of siRNA duplexes was carried out as described for Fig. 1. Twenty-four hours after transfection, culture medium was replaced with DMEM with (A) or without (B) 10% serum. Seventy-two hours after transfection, cell viability was examined by means of MTS assay. Cell viability in the presence of siRNA duplexes against *App*, *Aplp1*, and *Aplp2* was normalized against that in the presence of siControl. Data are means of three independent experiments. Error bars represent standard deviations.

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NEW METHODS AND TECHNOLOGIES

Assessment of allele-specific gene silencing by RNA interference with mutant and wild-type reporter alleles

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ABSTRACT

Allele-specific gene silencing by RNA interference (RNAi) is therapeutically useful for specifically suppressing the expression of alleles associated with disease. To realize such allele-specific RNAi (ASP-RNAi), the design and assessment of small interfering RNA (siRNA) duplexes conferring ASP-RNAi is vital, but is also difficult. Here, we show ASP-RNAi against the Swedish- and London-type amyloid precursor protein (*APP*) variants related to familial Alzheimer's disease using two reporter alleles encoding the *Photinus* and *Renilla* luciferase genes and carrying mutant and wild-type allelic sequences in their 3'-untranslated regions. We examined the effects of siRNA duplexes against the mutant alleles in allele-specific gene silencing and off-target silencing against the wild-type allele under heterozygous conditions, which were generated by cotransfecting the reporter alleles and siRNA duplexes into cultured human cells. Consistently, the siRNA duplexes determined to confer ASP-RNAi also inhibited the expression of the *bona fide* mutant APP and the production of either amyloid β 40- or 42-peptide in Cos-7 cells expressing both the full-length Swedish- and wild-type *APP* alleles. The present data suggest that the system with reporter alleles may permit the preclinical assessment of siRNA duplexes conferring ASP-RNAi, and thus contribute to the design and selection of the most suitable of such siRNA duplexes.

KEYWORDS: *RNAi, allele-specific gene silencing, amyloid precursor protein, Swedish mutation, London mutation, reporter allele*

INTRODUCTION

RNA interference (RNAi) is a powerful tool for suppressing the expression of a gene of interest (Dykxhoorn et al, 2003; Meister and Tuschl, 2004; Mello and Conte, 2004). In mammals, RNAi can be induced by direct introduction of synthetic small interfering RNA (siRNA) duplexes into cells or generation of siRNA duplexes using short-hairpin RNA expression vectors and its application is expanding to various fields of science; therapeutic use of RNAi in medical science and pharmacogenesis is particularly promising (Caplen, 2004; Dykxhoorn et al, 2003; Hannon and Rossi, 2004; Karagiannis and El-Osta, 2005; Wood et al, 2003). Allele-specific gene silencing by RNAi (allele-specific RNAi: ASP-RNAi) is an advanced application of RNAi techniques, by which the expression of an allele of interest can be inhibited (Victor et al, 2002). Accordingly, ASP-RNAi is thought to be therapeutically useful, i.e., it can specifically suppress the expression of alleles causing disease without inhibiting the expression of corresponding wild-type alleles. To realize and control such ASP-RNAi, the following issues must be addressed: selection of competent siRNA duplexes that strongly induce ASP-RNAi; and qualitative and quantitative evaluation of allele-specific gene silencing.

In this article, we describe an easy assay system for assessment of ASP-RNAi with mutant and wild-type reporter alleles encoding the *Photinus* and *Renilla luciferase* genes. Using the amyloid precursor protein

(*APP*) variants (the Swedish- and London-type variants) related to familial Alzheimer's disease (Goate et al, 1991; Mullan et al, 1992) as model mutant alleles, we determined the effects of siRNA duplexes against the mutant *APP* on allele-specific silencing as well as off-target silencing against the wild-type allele. The siRNA duplexes having the potential to specifically suppress the expression of the mutant reporter allele consistently inhibited the expression of the *bona fide* mutant APP as well as amyloid β 40- and 42-peptides in Cos-7 cells expressing both the full-length Swedish- and wild-type *APP* alleles. These observations suggest that the present system could permit the selection of siRNA duplexes having the potential to confer ASP-RNAi.

MATERIALS AND METHODS

Preparation of oligonucleotides

DNA and RNA oligonucleotides were obtained from INVITROGEN and TAKARA, respectively. For preparation of duplexes, sense- and antisense-stranded oligonucleotides (20 μM each) were mixed and annealed as described previously (Hohjoh, 2002). The sequences of synthesized oligonucleotides are shown in Tables 1 and 2. Non-silencing siRNA duplex (siControl; Qiagen) was used as a negative control.

Cell culture

HeLa, T98G and Cos-7 cells were grown at 37°C in Dulbecco's modified Eagle's medium (Wako) supplemented with 10% fetal bovine serum (Sigma), 100 U/ml penicillin and 100 μg/ml streptomycin (Sigma) in 5% CO_2-humidified chamber. T98G cells (Registry No. IFO50295) were obtained from the Health Science Research Resources Bank.

Construction of reporter and expression plasmids

In order to construct plasmids carrying reporter alleles, the phRL-TK (Promega) and pGL3-TK (Ohnishi et al., 2005) plasmids encoding the *Renilla* and *Photinus* luciferase genes, respectively, both of which were driven by the same herpes simplex virus thymidine kinase (TK) promoter, were digested with Xba I and Not I, and were subjected to ligation with synthetic oligonucleotide duplexes corresponding to the Swedish-, London- and wild-type *APP* alleles (sequences of the oligonucleotides used are indicated in Table 1). The resultant plasmids carry allelic *APP* sequences in the 3'-untranslated regions (UTRs) of the luciferase genes (Figure 1A). Expression plasmids, $pAPP695_{WT}$ and $pAPP695_{SWE}$ encoding full-length cDNAs of the wild- and Swedish-type *APP* alleles, respectively, were kindly provided by Dr Tanahashi (Tanahashi and Tabira, 2001).

Transfection and reporter assay

The day before transfection, cells were trypsinized, diluted with fresh medium without antibiotics, and seeded into 24-well culture plates (approximately 0.5×10^5 cells/well). Cotransfection of synthetic siRNA duplexes with reporter plasmids was carried out using Lipofectamine 2000 transfection reagent (Invitrogen) according to the manufacturer's instructions, and to each well, 0.24 μg (40 nM) of siRNA duplexes, 0.2 μg of pGL3-TK-backbone plasmid, 0.05 μg of phRL-TK-backbone plasmid and 0.1 μg of pSV-β-Galactosidase control vector (Promega) were applied. Twenty-four hours after transfection, cell lysate was prepared and expression levels of luciferase and β-Galactosidase were examined by the Dual-Luciferase reporter assay system (Promega) and Beta-Glo assay system (Promega), respectively, according to the manufacturer's instructions. In the case of transfection of siRNA duplexes and expression plasmids ($pAPP695_{WT}$ and $pAPP695_{SWE}$) into Cos-7 cells, 0.4 μg of each plasmid and 0.24 μg of siRNA duplexes were applied. Forty-eight hours after transfection, culture media was collected and cell lysate was prepared.

Western blotting and ELISA

Culture media and cell lysate prepared from transfected Cos-7 cells were examined by western blotting as described previously (Lesne et al., 2003). Equal amounts of proteins were separated by SDS-PAGE and electrophoretically blotted onto PVDF membranes (Millipore). Membranes were blocked for 1 h in blocking solution (5 % (v/w) fat-free milk and 0.05 % (v/v) Tween-20 in PBS) and

Table 1. Synthetic DNA oligonucleotides

Name	Sequence (5'----------3')
ssAPPwt(Sw)	CTAGCATGCAGGAGATCTCTGAAGTGAAGATGGATGCAGAATTCCGACA
asAPPwt(Sw)	GGCCTGTCGGAATTCTGCATCCATCTTCACTTCAGAGATCTCCTGCATG
ssAPP(K670N-M671L)	CTAGCATGCAGGAGATCTCTGAAGTGAATCTGGATGCAGAATTCCGACA
asAPP(K670N-M671L)	GGCCTGTCGGAATTCTGCATCCAGATTCACTTCAGAGATCTCCTGCATG
ssAPPwt(Lo)	CTAGCATGCTGTCATAGCGACAGTGATCGTCATCACCTTGGTGATGCTGA
asAPPwt(Lo)	GGCCTCAGCATCACCAAGGTGATGACGATCACTGTCGCTATGACAGCATG
ssAPP(V717I)	CTAGCATGCTGTCATAGCGACAGTGATCATCATCACCTTGGTGATGCTGA
asAPP(V717I)	GGCCTCAGCATCACCAAGGTGATGATGATCACTGTCGCTATGACAGCATG
ssAPP(V717F)	CTAGCATGCTGTCATAGCGACAGTGATCTTCATCACCTTGGTGATGCTGA
asAPP(V717F)	GGCCTCAGCATCACCAAGGTGATGAAGATCACTGTCGCTATGACAGCATG
ssAPP(V717G)	CTAGCATGCTGTCATAGCGACAGTGATCGGCATCACCTTGGTGATGCTGA
asAPP(V717G)	GGCCTCAGCATCACCAAGGTGATGCCGATCACTGTCGCTATGACAGCATG

Table 2. Synthetic siRNAs used in this study. Sense- and antisense-stranded siRNA elements are indicated by '-ss' and '-as', respectively.

siRNAs against the Swedish *APP* mutant	
Name	**Sequence (5'----------3')**
si(T7/C8)-ss	AGUGAAUCUGGAUGCAGAAUUU
si(T7/C8)-as	AUUCUGCAUCCAGAUUCACUUU
si(T8/C9)-ss	AAGUGAAUCUGGAUGCAGAAUU
si(T8/C9)-as	UUCUGCAUCCAGAUUCACUUUU
si(T9/C10)-ss	GAAGUGAAUCUGGAUGCAGAUU
si(T9/C10)-as	UCUGCAUCCAGAUUCACUUCUU
si(T10/C11)-ss	UGAAGUGAAUCUGGAUGCAGUU
si(T10/C11)-as	CUGCAUCCAGAUUCACUUCAUU
si(T11/C12)-ss	CUGAAGUGAAUCUGGAUGCAUU
si(T11/C12)-as	UGCAUCCAGAUUCACUUCAGUU
si(T12/C13)-ss	UCUGAAGUGAAUCUGGAUGCUU
si(T12/C13)-as	GCAUCCAGAUUCACUUCAGAUU
siRNAs against the London *APP* mutants	
Name	**Sequence (5'----------3')**
si(A8)-ss	AGUGAUCAUCAUCACCUUGUU
si(A8)-as	CAAGGUGAUGAUGAUCACUUU
si(A9)-ss	CAGUGAUCAUCAUCACCUUUU
si(A9)-as	AAGGUGAUGAUGAUCACUGUU
si(A10)-ss	ACAGUGAUCAUCAUCACCUUU
si(A10)-as	AGGUGAUGAUGAUCACUGUUU
si(A11)-ss	GACAGUGAUCAUCAUCACCUU
si(A11)-as	GGUGAUGAUGAUCACUGUCUU
si(A12)-ss	CGACAGUGAUCAUCAUCACUU
si(A12)-as	GUGAUGAUGAUCACUGUCGUU
si(T8)-ss	AGUGAUCUUCAUCACCUUGUU
si(T8)-as	CAAGGUGAUGAAGAUCACUUU
si(T9)-ss	CAGUGAUCUUCAUCACCUUUU
si(T9)-as	AAGGUGAUGAAGAUCACUGUU
si(T10)-ss	ACAGUGAUCUUCAUCACCUUU
si(T10)-as	AGGUGAUGAAGAUCACUGUUU
si(T11)-ss	GACAGUGAUCUUCAUCACCUU
si(T11)-as	GGUGAUGAAGAUCACUGUCUU
si(T12)-ss	CGACAGUGAUCUUCAUCACUU
si(T12)-as	GUGAUGAAGAUCACUGUCGUU
si(G8)-ss	GUGAUCGGCAUCACCUUGGUU
si(G8)-as	CCAAGGUGAUGCCGAUCACUU
si(G9)-ss	AGUGAUCGGCAUCACCUUGUU
si(G9)-as	CAAGGUGAUGCCGAUCACUUU
si(G10)-ss	CAGUGAUCGGCAUCACCUUUU
si(G10)-as	AAGGUGAUGCCGAUCACUGUU
si(G11)-ss	ACAGUGAUCGGCAUCACCUUU
si(G11)-as	AGGUGAUGCCGAUCACUGUUU
si(G12)-ss	GACAGUGAUCGGCAUCACCUU
si(G12)-as	GGUGAUGCCGAUCACUGUCUU

were incubated with anti-APP antibody 22C11 (Chemicon) or anti-α-tubulin antibody DM1A (Sigma) followed by washing in PBS and further incubation with horseradish peroxidase-conjugated donkey anti-mouse IgG (Jackson ImmunoResearch Laboratories). Antigen-antibody complexes were visualized using ECL chemiluminescent reagent (Amersham). Levels of Aβ40 and Aβ42 production in culture media were examined by human/rat β amyloid 40 and 42 ELISA kits (Wako) according to the manufacturer's instructions.

RT-PCR

Total RNA extraction, including treatment with DNase I (Ambion) twice followed by reverse transcription, were carried out as described previously (Sago et al., 2004). The resultant cDNAs were examined by real-time (RT)-PCR using the ABI PRISM 7300 sequence detection system (Applied Biosystems) with a SYBER green PCR master mix (Applied Biosystems) according to the manufacturer's instructions. PCR primers used were as follows:

For detection of the *Renilla luciferase* transcript:

renilla-F; 5'-GTTCTTTTCCAACGCTATTG-3'
renilla-R; 5'-GAAGCTCTTGATGTACTTAC-3'

For detection of the *Photinus luciferase* transcript:

photinus-F; 5'-TTTGATATGTGGATTTCGAG-3'
photinus-R; 5'-ATCGTATTTGTCAATCAGAG-3'

RESULTS

Assessment of siRNAs in heterozygous model system

In this study, the Swedish- and London-type mutants of the *APP* gene, which are involved in familial Alzheimer's disease, were used as model mutant alleles. The Swedish- and London-type *APP* mutants carry double and single nucleotide substitutions, respectively, which are followed by amino acid substitutions (K670N-M671L in the Swedish APP; V717I, V717F or V717G in the London APP) (Goate et al, 1991; Mullan et al, 1992). The resultant amino acid sequences in the Swedish and London-type APPs are preferably digested by β- and γ-secretase, respectively, resulting in accumulation of Aβ40 and Aβ42 peptides, which are the key factors of Alzheimer's disease (Cai et al, 1993; Citron et al, 1992; Mattson, 2004; Suzuki et al, 1994).

Mutant and wild-type reporter alleles were constructed as described in Materials and Methods. The resultant reporter alleles (Figure 1A), synthetic siRNA duplex against the mutant allele and the *β-galactosidase* gene (control) were cotransfected into human cells. Note that the transfected cells are artificially heterozygous with the mutant and wild-type *APP* reporter alleles; thus, the effects of test siRNA duplexes on suppression of both the mutant and wild-type alleles can be simultaneously examined.

ASP-RNAi against the Swedish-type APP allele

When the *Renilla* and *Photinus luciferase* genes were regarded as the Swedish and wild-type reporter alleles, respectively, the effects of the si(T7/C8) - si(T12/C13) duplexes against the Swedish mutant on allele-specific gene silencing were examined in HeLa cells. The results

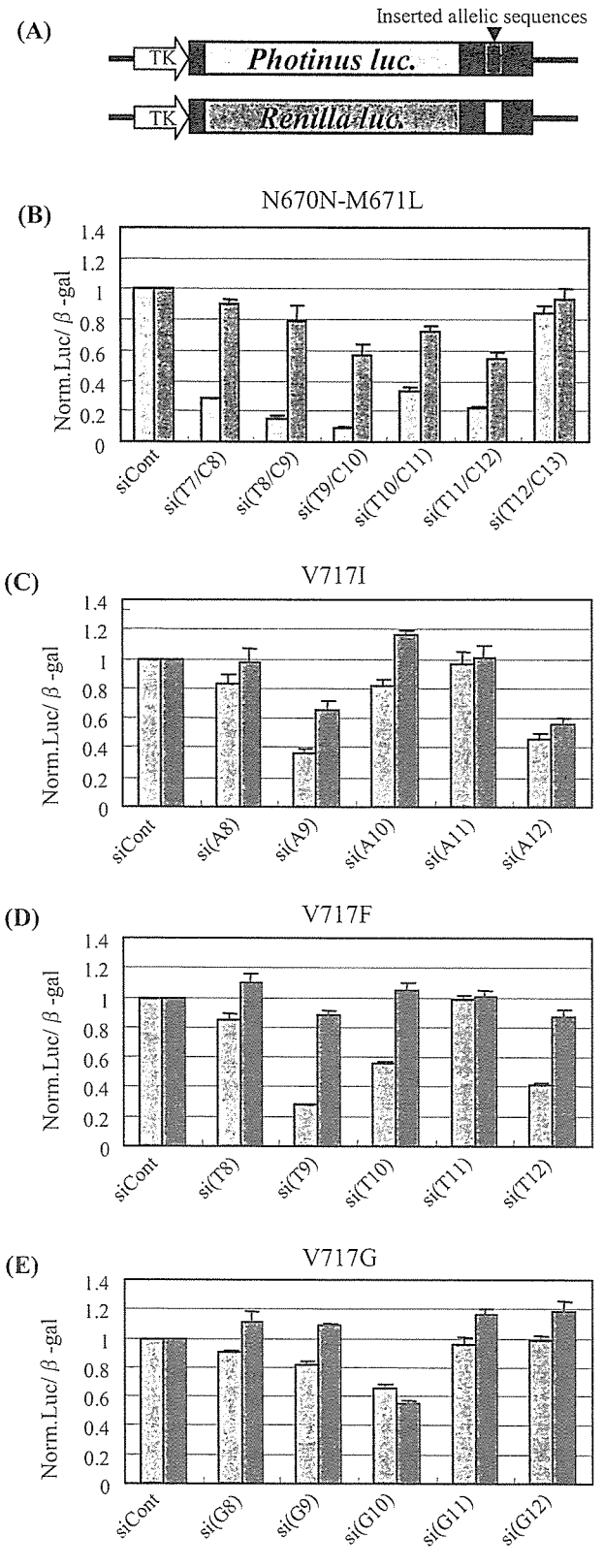

Figure 1. Assessment of ASP-RNAi with reporter alleles. (**A**) Schematic drawing of reporter alleles. Reporter alleles were constructed based on the *Photinus* and *Renilla luciferase* reporter genes driven by the same TK promoter, and allelic sequences of wild-type and mutant (synthetic oligonucleotides) were inserted into the 3'-UTRs of the reporter genes, i.e., the reporter alleles encode *luciferase* reporter genes carrying artificially inserted allele sequences of interest. Assessment of siRNA duplexes on the induction of ASP-RNAi against the Swedish *APP* mutant (**B**) and against the London APP mutants (**C-E**) was carried out. Synthetic siRNA duplexes against the mutants indicated were cotransfected with the mutant and wild-type reporter alleles and the *β-galactosidase* gene (control) into HeLa cells. The *Photinus* and *Renilla luciferase* genes carry the mutant and wild-type allelic sequences, respectively. Twenty-four hours after transfection, dual-luciferase and β-galactosidase assays were carried out. The levels of either *Photinus* (blue boxes) or *Renilla* (pink boxes) luciferase activity was normalized against the levels of β-galactosidase activity, and the ratios of mutant and wild-type luciferase activities in the presence of siRNA duplexes were normalized against the control ratio obtained in the presence of the siControl duplex (siCont). Data are averages of at least three independent determinations. Error bars represent standard deviations.

are shown in Figure 1B. The siRNA duplexes, except for the si(T12/C13) duplex, appeared to induce inhibition of mutant (*Photinus*) allele expression, while little or moderate inhibition of wild-type (*Renilla*) allele expression was seen, suggesting that the siRNA duplexes were able to discriminate the mutant reporter allele from the wild-type reporter allele. The si(T12/C13) duplex appeared to yield little or no RNAi activity. Considering the influence of the siRNA duplexes on the expression of the wild-type allele, the si(T8/C9) duplex appears to be the most suitable siRNA duplex conferring ASP-RNAi against the mutant allele. As for the si(T9/C10) and si(T11/12) duplexes inducing moderate levels of inhibition of wild-type allele expression, further analyses were carried out (Figure 4). Similar results were also obtained when the luciferase genes were exchanged between the mutant and wild-type reporter alleles, i.e., the *Photinus* and *Renilla luciferase* genes carried the wild-type and Swedish allele sequences, respectively (data not shown). In addition, when T98G cells, a human glioblastoma cell line, and Cos-7 cells were used instead of HeLa cells, results similar to those obtained in HeLa cells were observed (data not shown).

ASP-RNAi against London-type APP alleles

Because the London-type mutant possesses three types of single nucleotide change involved in amino acid substitution at position 717 (V717I, V717F and V717G), three mutant reporter alleles and corresponding wild-type reporter allele were constructed, and the effects of synthetic siRNA duplexes against the London-type mutants on suppression of the expression of either the target mutant allele or wild-type allele were examined under the present system. As shown in Figure 1C-E, various levels of gene silencing were observed and some of the siRNA duplexes, si(T9) and si(T12) (Figure 1D), appeared to discriminate the mutant alleles from the wild-type allele to some degree, resulting in ASP-RNAi; however, the other siRNA duplexes examined yielded less significant ASP-RNAi. Compared with the results for ASP-RNAi against the Swedish allele (Figure 1B), the induction and activation of ASP-RNAi against the London alleles appeared to be inferior to those against the Swedish mutant.

Western blot analyses of wild-type and Swedish APP in ASP-RNAi

We further investigated ASP-RNAi of siAPP duplexes against the Swedish mutant with full-length cDNAs of the Swedish and wild-type *APP* alleles, which were transiently

expressed in Cos-7 cells. The pAPP695$_{SWE}$ and/or pAPP695$_{WT}$ expression plasmids encoding full-length cDNAs of the Swedish and wild-type *APP* alleles, respectively, and siRNA duplexes targeting the Swedish mutant were cotransfected into Cos-7 cells, and expression of wild-type APP (APP$_{WT}$) and Swedish APP (APP$_{SWE}$) was examined by Western blotting. As shown in Figure 2, under homo(or hemi)zygous-like conditions, in which either APP$_{WT}$ or APP$_{SWE}$ was expressed, the signal intensity of sAPP$_{SWE}$ (secreted APP) and cAPP$_{SWE}$ (celluar APP) was apparently decreased in the presence of the si(T8/C9), si(T9/C10) and si(T11/C12) duplexes. In contrast, signals for either sAPP$_{WT}$ or cAPP$_{WT}$ were detected in the presence of any of the siRNA duplexes examined, which is consistent with the data for the reporter alleles described above. When APP$_{SWE}$ and APP$_{WT}$ were both expressed in the cells (heterozygous-like conditions), signals for APP were seen in the presence of any of the siRNA duplexes. Based on the results under homozygous-like conditions, the signals for APP in the presence of the si(T8/C9), si(T9/C10) and si(T11/C12) duplexes were most likely derived from APP$_{WT}$.

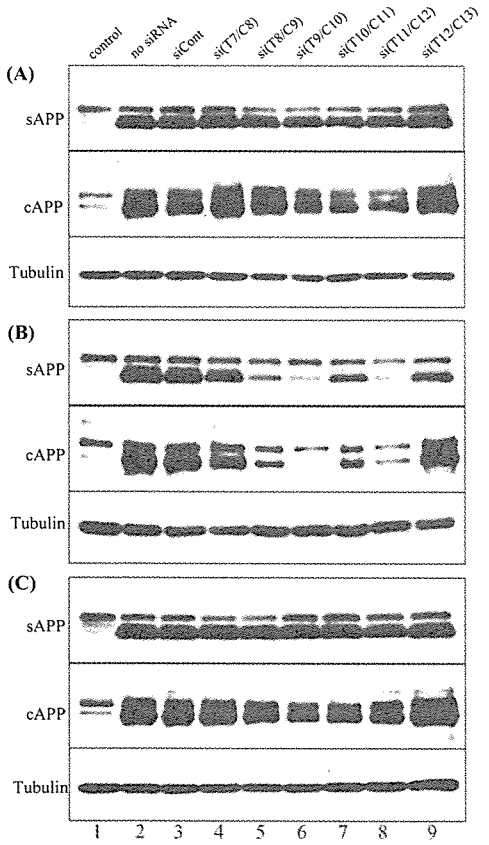

Figure 2. Expression of APP$_{WT}$ and APP$_{SWE}$ polypeptides under ASP-RNAi. Either the pAPP695$_{WT}$ (**A**) and pAPP695$_{SWE}$ (**B**) expression plasmids or the plasmids (**C**) together with the indicated siRNA duplexes against the Swedish mutant were introduced into Cos-7 cells, and expressed APP polypeptides in culture media (secreted APP: sAPP) and in cells (cellar APP: cAPP) were examined by Western blotting. Lane 1 (control) shows no transfected Cos-7 cells, in which endogenous APP is detectable. Lanes 2-9 are cells transfected with expression plasmid(s), and lanes 3-9 are cotransfected cells with the indicated siRNA duplexes. Expression of α-tubulin (control) is also shown.

The utility of ASP-RNAi using the siRNA duplexes assessed here in medical treatment can be demonstrated by confirming a significant decrease in Aβ peptides, which are a key factor in the development of Alzheimer's disease under heterozygous conditions expressing both APP$_{SWE}$ and APP$_{WT}$. We thus determined the production levels of Aβ40 and Aβ42 peptides by means of ELISA. As shown in Figure 3, significant decreases in the production of either Aβ40 or Aβ42 peptide by RNAi (Figure 3A-C) and ASP-RNAi (Figure 3D-F) with the evaluated siRNA duplexes, particularly si(T8/C9), si(T9/C10) and si(T11/C12), was confirmed under homozygous and heterozygous conditions, respectively. Therefore, these results suggest the potential utility of such siRNA duplexes as therapeutic agents.

DISCUSSION

While ASP-RNAi is believed to be a useful technique, to realize and control ASP-RNAi, it is vital to design and select competent siRNA duplexes conferring ASP-RNAi; however, this is rather difficult without a procedure for assessing such siRNA duplexes. The system we present here could allow assessment, if designed siRNA duplexes have the potential for specifically inhibiting the expression of target alleles without suppressing the expression of other alleles. From a series of experiments with the Swedish- and London-type APP variants as model mutant alleles, we were able to determine potential siRNA duplexes for inducing ASP-RNAi. With regard to siRNA duplexes targeting the Swedish mutant, we further demonstrated that the si(T8/C9), si(T9/C10) and si(T11/C12) siRNA duplexes were able to significantly decrease the production of either Aβ40 or Aβ42 peptide in Cos-7 cells expressing both the full-length Swedish- and wild-type *APP* alleles. Accordingly, such competent siRNA duplexes conferring ASP-RNAi against mutant alleles likely hold utility as therapeutic agents.

In contrast to the Swedish mutant, there were difficulties in suppressing the London-type mutants carrying single nucleotide substitutions from the wild-type allele by ASP-RNAi. The difference between ASP-RNAi activities against the Swedish- and London-type mutants may have been caused by the number of base substitutions: the former and latter mutants carry double and single base substitutions, respectively. Another important point to note in the results for the London-type mutant is that different substitutions showed different ASP-RNAi activities, suggesting that the type of base change between the mutant and wild-type alleles could influence ASP-RNAi. With regard to the V717I (Figure 1C) and V717G (Figure 1E) mutants, a possible wobble base pair between siRNA and the wild-type mRNA (Du et al, 2005) and high GC content of siRNA used(Ui-Tei et al, 2004), respectively, might have negatively influenced the induction of ASP-RNAi; these possibilities require further examination in the future.

To further progress ASP-RNAi, it is necessary to design competent siRNA duplexes conferring strong allele-specific gene silencing. Chemical modifications (Chiu and Rana, 2003; Hall et al, 2004) and structural devices in siRNAs are considered to be applicable for improving

ASP-RNAi, and assessment of such siRNAs is feasible using the system we presented here. Altogether, it is suggested that the present assay system may contribute to the design and selection of the most suitable of siRNA duplexes conferring ASP-RNAi.

Finally, we add data indicating the possible inhibition of wild-type allele translation by the present siRNA duplexes. Because si(T9/C10) and si(T11/C12) exhibited moderate levels of inhibition of the expression of wild-type reporter allele (Figure 1B), we further investigated RNA levels of the wild-type allele by RT (real-time)-PCR. As shown in Figure 4, the levels of RNA expression of the wild-type allele in the presence of si(T9/C10) were similar to those in the presence of siControl, suggesting the possible inhibition of translation of the wild-type allele by the si(T9/C10) duplex. This may be due to a microRNA-like effect (Poy et al, 2004; Tang, 2005), and further study into this possibility remains necessary. With regard to the si(T11/C12) duplex, because a decrease trend in the levels of wild-type allele transcript was seen, it is possible that off-target gene silencing (Jackson et al, 2003) of the wild-type allele may occur in the presence of the duplex. Consequently, it is conceivable that the present system could further contribute to studies into off-target gene silencing and the function of microRNAs.

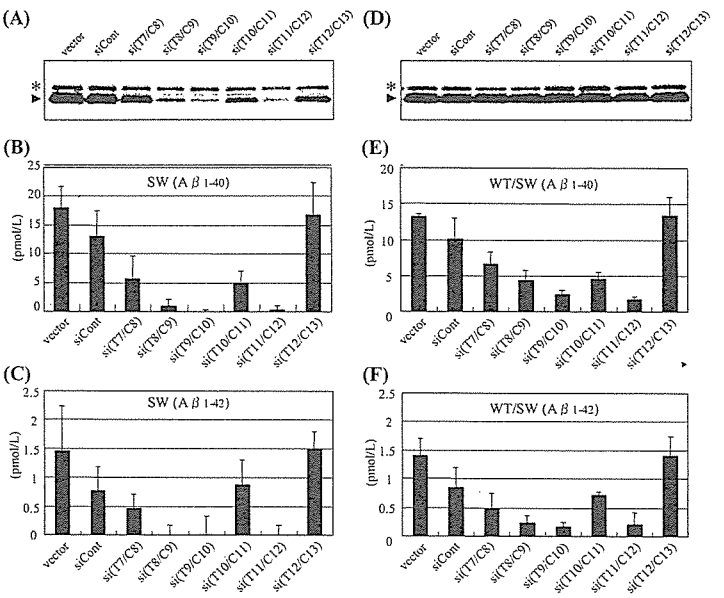

Figure 3. Production of Aβ40 and Aβ42 peptides under ASP-RNAi. The pAPP695$_{SWE}$ (**A-C**) plasmid and both the pAPP695$_{SWE}$ and pAPP695$_{WT}$ (**D-F**) plasmids together with the indicated siRNA duplexes against the Swedish mutant were cotransfected into Cos-7 cells, and expressed sAPP polypeptide and Aβ40 and Aβ42 peptides in culture media were examined by western blotting (**A, D**) and ELISA (**B, C, E, F**), respectively. "Vector" indicates cells transfected with only plasmid(s). Endogenous and exogenous (expressed) sAPPs are indicated by asterisks and arrow heads, respectively. ELISA data are averages of three independent determinations. Error bars represent standard deviations.

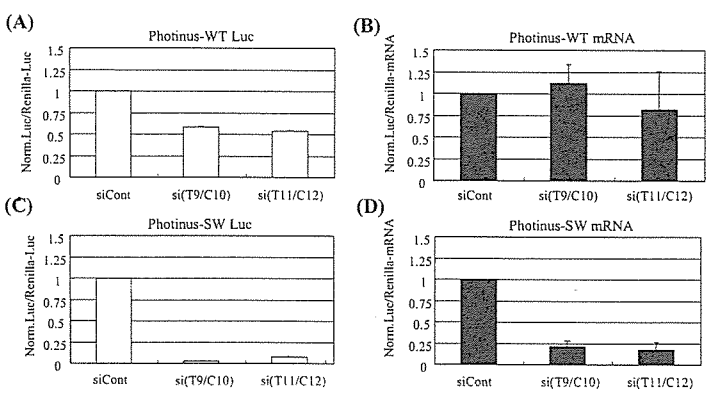

Figure 4. Possible translation inhibition and off-target silencing of wild-type reporter allele by siAPP duplexes. The si(T9/C10) or si(T11/C12) duplexes against the Swedish mutant allele together with either wild or mutant reporter allele plasmid carrying *Photinus luciferase* and the phRL-TK plasmid encoding *Renilla luciferase* (control) were introduced into HeLa cells. Twenty-four hours after transfection, dual-luciferase assay and isolation of total RNA were carried out. Off-target (to wild-type reporter allele) (**A**) and on-target (RNAi; to mutant reporter allele) (**C**) gene silencing were assessed based on luciferase activities. Ratios of normalized target (Photinus) luciferase activity to control (Renilla) luciferase activity are indicated: the ratios of luciferase activity determined in the presence of the si(T9/C10) or si(T11/C12) duplexes were normalized against the ratios obtained in the presence of the siControl duplex (siCont). Isolated RNAs in (**B**) and (**D**) corresponding to (**A**) and (**C**), respectively, were subjected to reverse transcription to

synthesize first-stranded cDNAs. The resultant cDNAs were examined by real-time PCR with specific primers for *Photinus* and *Renilla luciferase*. RNA expression levels for *Photinus luciferase* are normalized against those of *Renilla luciferase*, and the ratios of *Photinus luciferase* RNA expression levels in the presence of the si(T9/C10) or si(T11/C12) duplexes are normalized against the ratios obtained in the presence of the siControl duplex. Data are averages of at least three independent determinations. Error bars represent standard deviations.

CONCLUSIONS

The present assay system with wild-type- and mutant-reporter alleles could permit assessment of siRNA duplexes having the potential for specifically inhibiting the expression of the mutant allele without inhibiting the expression of the wild-type allele, and thus contribute to the design and selection of siRNA duplexes suitable for allele-specific gene silencing.

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STATEMENT OF COMPETING INTERESTS

Corresponding author has a pending patent on the method of this paper.

LIST OF ABBREVIATIONS

ASP-RNAi; Allele-specific RNA interference
APP; Amyloid precursor protein
TK; Thymidine kinase
UTR; Untranslated region
sAPP; Secreted APP
cAPP; Celluar APP
Aβ; Amyloid β

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