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siRNA-based inhibition specific for mutant SOD1 with single nucleotide alternation in familial ALS, compared with ribozyme and DNA enzyme☆,☆☆

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Abstract

In many of autosomal dominant diseases such as familial amyotrophic lateral sclerosis (ALS) with SOD1 mutation, a missense point mutation may induce the disease by its gain of adverse property. Reduction of such a mutant protein expression is expected to improve the disease phenotype. Duplex of 21-nt RNA, known as siRNA, has recently emerged as a powerful tool to silence gene, but the sequence specificity and efficacies have not been fully studied in comparison with ribozyme and DNA enzyme. We could make the siRNA which recognized even a single nucleotide alternation and selectively suppress G93A SOD1 expression leaving wild-type SOD1 intact. In mammalian cells, the siRNA much more efficiently suppressed the expression of mutant SOD1 than ribozyme or DNA enzyme. Furthermore, these siRNAs could suppress cell death of Neuro2a induced by over-expression of mutant SOD1s with stress of proteasome inhibition. Our results support the feasibility of utilizing siRNA-based gene therapy of familial ALS with mutant SOD1.

Amyotrophic lateral sclerosis (ALS) is characterized by the degeneration of "lower motor neurons" in the spinal cord and brainstem, and degeneration of the descending motor pathway in the corticospinal tracts. Although most cases of ALS are sporadic and have an unknown etiology, 5–10% of ALS cases are familial, and of these, approximately 20% are due to missense, point mutations in the gene encoding Cu,Zn-superoxide dismutase (SOD1) [1]. Recent studies with transgenic mice and cell culture models of ALS with SOD1 mutations indicated that SOD1 mutations induce the disease by its toxic property, not by a loss of the SOD1 activity [2,3]. Similar 'gain of toxic function' of mutant protein is predicted to cause cell death in other autosomal dominant neurodegenerative diseases with a missense point mutation, such as familial Alzheimer's disease, prion disease, and Parkinson's disease. In all these familial diseases, one rational approach to therapy is to develop a method to specifically eliminate the aberrant protein.

RNA interference (RNAi) is the process of sequence-specific, post-transcriptional gene silencing, initiated by double-stranded RNA (dsRNA). This has a multi-step process that involves generation of 21–23 nt small interfering RNA (siRNA), resulting in degradation of the homologous RNA [4]. In mammalian cells, however, this provokes a strong cytotoxic response, leading to the

☆ *Abbreviations:* ALS, amyotrophic lateral sclerosis; SOD, superoxide dismutase; siRNA, small interfering RNA; dsRNA, double-stranded RNA; rAAVs, recombinant adeno-associated viruses.

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non-specific degradation of RNA transcripts and a general shut down of host cell protein translation [5,6]. This problem has been recently overcome by use of in vitro-synthesized siRNA, which is long enough to mediate gene-specific suppression, but short enough to evade adverse effects of long dsRNA [5].

Ribozymes and DNA enzyme are also small RNA/DNA molecules that possess sequence-specific RNA cleavage activity. Ribozymes occur naturally, but can also be created artificially to target specific sequences in *cis* or *trans* (i.e., on the same molecule or on a different molecule). They recognize and cleave a specific target sequence motif, 5′-NUX (where N is any nucleotide; X is A, C, or U) [7]. DNA enzyme or deoxyribozyme was derived by in vitro selection from a combinatorial library of DNA sequence and has a potential to cleave RNA at any purine (A, G)–pyrimidine (C, U) junction [8]. Both of ribozyme and DNA enzyme consist of a Mg^{2+}-dependent catalytic domain flanked by two substrate-binding arms and cleave a specific phosphodiester linkage of target RNA without recruiting endogenous nuclease. Ribozymes and DNA enzymes also can discriminate even a single nucleotide mismatch and have been successfully used to target and destroy specific RNAs. However, there was no report in which the specificity and efficiency of siRNA were directly compared with those of ribozyme and DNA enzyme.

In the present report, we have engineered siRNAs and DNA-based expressing siRNAs for mutant and wild-type SOD1s, to evaluate their efficiencies in comparison with ribozyme and DNA enzyme to decrease the expression of mutant SOD1 protein as a potential method for gene therapy of familial ALS.

Materials and methods

siRNA and DNA-vector based expressing siRNA preparation. The targeted region of siRNA was the coding sequence of SOD1 cDNA. The 5′ or 3′ UTRs and regions nearby the start codon are avoided, as these may be richer in regulatory protein binding sites. siRNA sequences of the form AA N_{19-20} and CA N_{19-20} with GC content less than 70% were selected from this region [9]. Next, the nucleotide preference after AA/CA is G or A, because it is required for efficient RNA polymerase initiation. Selected 19- or 20-nucleotide RNAs followed by TT or TdG were chemically synthesized and gel-purified. Synthesized single strand oligonucleotides were annealed at 95 °C for 1 min followed by slow cooling in the annealing buffer (PBS, pH 6.8, 2 mM $MgCl_2$).

siRNA-expressing vectors were made by modified reported methods using stem-loop type of siRNA [10,11]. The stem-loop type vector contains siRNA hairpin which contains 20–21 nt sense and antisense sequences of siRNA, connected by 3′ end of the sense strand and 5′ end of the antisense strand by a 9-nt loop sequence. Inserts containing the 9-nt loop sequence (TTCAAGAGA) flanked by sense and antisense siRNA sequences were made by PCR. These were inserted immediately downstream of U6 promotor in pUC19 [12].

Construction of plasmids encoding the substrate RNA and ribozymes. For target coding sequence cDNA clones of the human wild-type SOD1 and mutant A4V (kindly provided by T. Usdin) were used. Full-length human SOD1 cDNA was subcloned in the *Eco*RI and *Xba*I sites of pcDNA3 (Invitrogen). G93A, G93R, G93S, and G93C constructs were created using the QuikChange site-directed mutagenesis system from Stratagene. GFP–SOD1 fusion clones were constructed in *Eco*RI and *Sal*I sites of pEGFP-C2 (Clontech, Palo Alto, CA) using PCR method.

For a target site of hammerhead ribozyme, 5′-NUX (N = any nucleotide; X = A, U, or C) sequence [7] was selected. For the selection of DNA enzyme, purine–pyrimidine or AG [8] sequence was searched. DNA enzymes were chemically synthesized. Ribozyme coding sequences were made from two complementary synthetic DNA oligonucleotides flanked by *Xba*I and *Eco*RI restriction sites. These oligonucleotides were annealed and ligated into pcDNA3(−) (Invitrogen). Each ribozyme was followed by internally cleaving hairpin ribozyme [13].

Cell culture and transfection. Cells from the human embryonic kidney cell line 293T (293T) and mouse Neuro2a were cultured in Dulbecco's modified Eagle's medium containing 10% fetal bovine serum with 1% penicillin/streptomycin. Transient transfection using Lipofectamine Plus reagent (Life Technologies, Rockville, MD) was carried out in 24-well plates with cells reaching 40–60% confluence. Mutant or wild-type SOD1 expression plasmid (0.25 μg) and 2.5–125 nM (0.07–3.5 μg) siRNA, 0.5–2.0 μg DNA-vector-based expressing siRNAs, 10 μg DNA enzyme, or 1.0–2.0 μg ribozyme expression plasmid were transfected together with 0.05 μg GFP expression plasmid (pEGFP-C2; Clontech) to monitor for transfection efficiency. The medium for DNA enzyme was changed with fresh medium containing 1 μg DNA enzyme at 24 h after transfection. For control transfection of the same volume of siRNA, DNA enzyme for unrelated Machado-Joseph disease gene or empty pcDNA3 was used.

For fluorescence analysis, 0.25 μg GFP fused-mutant or wild-type SOD1 expression plasmids and 25 nM siRNA were transfected with 0.1 μg DsRed expression vector (pDsRed2; Clontech) to monitor for transfection efficiency. Cell was visualized with fluorescence microscopy (Nikon, Tokyo).

In vitro transcription and cleavage reactions by ribozyme and DNA enzyme. Plasmids containing target SOD1 sequences were linearized with *Xba*I, and plasmids containing ribozyme sequences with *Eco*RI. In vitro transcription was performed with 10 μg linear DNA template and T7 RNA polymerase using RiboMAX (Promega) and labeled by incorporation of [α-^{32}P]uridine triphosphate. After digesting DNA with DNase I, the transcripts were purified.

For standard cleavage reactions in vitro, 8 μM SOD1 substrate RNA and 40 μM ribozyme or 40 μM DNA enzyme were mixed in a 10 μl reaction buffer containing 20 mM $MgCl_2$ and 40 mM Tris–HCl (pH 7.5). The mixture was incubated at 37 °C for 1–4 h and stopped by addition of 50 mM EDTA, and then an equal volume of 10 M urea and 0.02% bromphenol blue. The cleavage products were denatured at 90 °C for 2 min and electrophoresed in 6% polyacrylamide–7 M urea gel in Tris–borate EDTA buffer.

Western blot analysis. At 24 or 48 h after transfection, cells were harvested by gentle scraping in lysis buffer (50 mM Tris–HCl, 150 mM NaCl, 1% Triton X, and a proteinase inhibitor cocktail, Complete (Roche)). Equal amounts of total cellular protein were mixed with 5× Laemmli sample buffer, denatured at 95 °C for 5 min, and separated on 15% SDS–polyacrylamide gels. Protein was transferred electrophoretically to polyvinylidene difluoride membranes, immunoblotted with anti-SOD1 polyclonal antibody S-100 (Stressgen Biotechnologies) and anti-GFP monoclonal antibody (Clontech), and detected using enhanced chemiluminescence (Amersham–Pharmacia Biotech).

All experiments of Western blotting were separately performed at least three times.

Cell-toxicity assay. Neuro2a cells in 24-well culture plates were co-transfected with mutant or wild-type SOD1 expression plasmid (1.0 μg/well), 25 nM siRNA (or 1.0 μg expressing siRNA vector), and pCMV-β-gal (50 ng/well) (Clontech). The medium was replaced with that containing 2 mM dibutyryl cyclic-AMP 3 h after transfection to

differentiate the cells. At 24 h after transfection, proteasome inhibitor, lactacystin (20 μM), was added to the medium. At 48 h, the cells were harvested and assayed with β-galactosidase assay kit (Promega). The LacZ expression levels correlate with cellular viability [14]. The percent viability was calculated in comparison with control lysates without lactacystin. Statistical significance was evaluated by single factor ANOVA (analysis of variance) or two-way ANOVA followed by Scheffe's method.

Results

Suppression effect of siRNA, DNA enzyme, and ribozyme specific for mutant SOD1 at codon 93

siRNA and expressing siRNA for G93A SOD1

Two siRNAs targeting G93A SOD1 corresponding to regions 277–297 (siRNA G93A.1) and 275–294 (siRNA G93A.2) were designed (Fig. 1A). Transfection of both siRNAs into mammalian cells could effectively reduce G93A SOD1 expression. Western blot analysis revealed that both siRNA G93A.1 and 2 reduced the expression of G93A SOD1 protein by about 90% when expression efficiency was adjusted with co-transfected GFP (Fig. 1B). The suppression of G93A SOD1 protein by siRNA G93A.1 increased in a dose-dependent manner when the amount of siRNA was changed from 2.5 to 125 nM (Fig. 1C). These siRNAs recognized only one nucleotide alteration, because they suppressed wild-type SOD1 protein much less than G93A SOD1—especially siRNA G93A.2, for which the reduction of wild type was only 1.8% (Fig. 1B). These suppression effects were confirmed by the reduction in GFP fluorescence when siRNA was co-transfected with a GFP-fused SOD1 plasmid (Fig. 1D) using DsRed fluorescence as a control for transfection efficiency (data not shown).

All these results were similarly confirmed in both 293T and Neuro2a cells.

DNA enzyme and ribozyme

We can design the G93A-specific DNA enzyme (Dz G93A) which cleaves G93A mutant SOD1 RNA, but not wild-type SOD1 RNA. Because the wild-type purine-purine sequence at G93A site (GGT) that is not recognized by the DNA enzyme is mutated to a

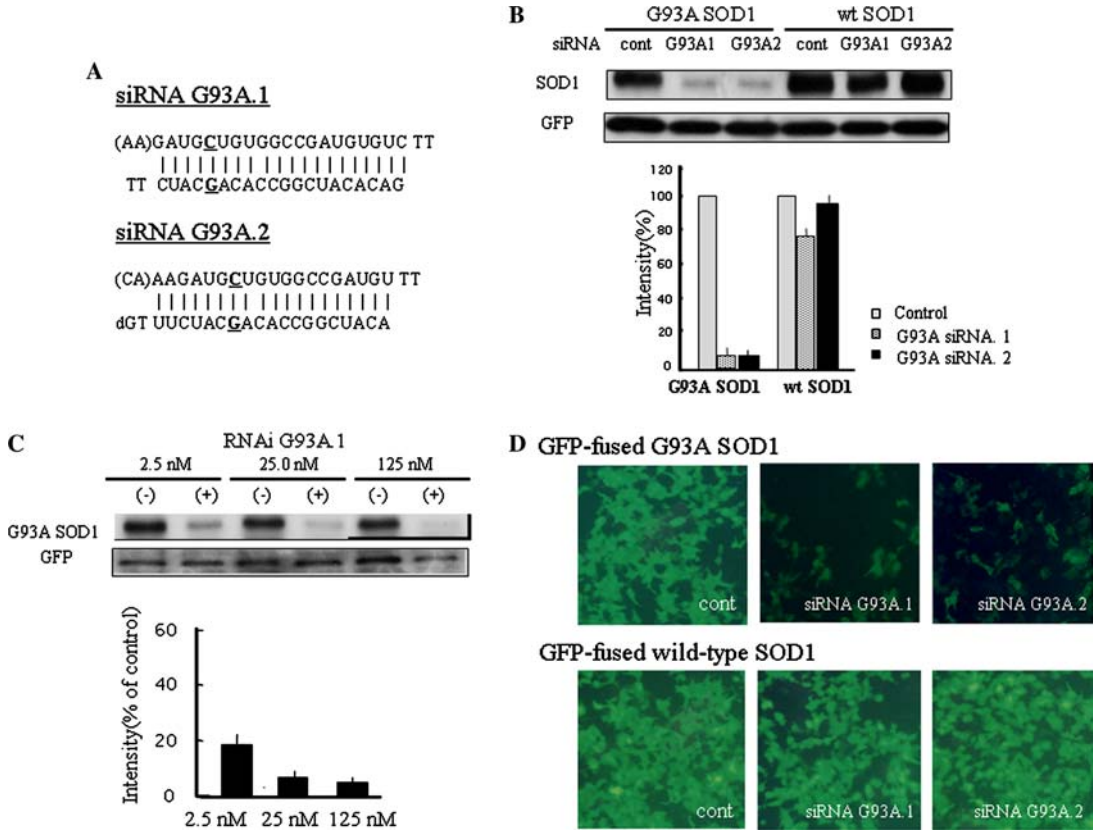

Fig. 1. siRNAs specific for G93A SOD1. (A) Sequences of siRNA G93A.1 and G93A.2. Underlined characters indicate mutations. (B) Effect of siRNA G93A.1 and 2 on G93A and wild-type SOD1 proteins (with no tag) expressed in 293T cells as detected by Western blotting with anti-SOD1 antibody. Expression level of target protein was adjusted by level of co-transfected GFP expression (B). Data are at 48 h after transfections. (C) Dose-dependent effect of suppression of siRNA G93A.1. Figure shows the percentages of band intensity with siRNA G93A.1 with respect to that with each mock transfection. (D) Effect of siRNA G93A.1 and 2 on fluorescence of GFP-fused SOD1s. Expression level of target protein was adjusted by level of co-transfected DsRed fluorescence (data not shown). Values are means and SEM.

purine–pyrimidine (GCT) sequence that is cleaved by the DNA enzyme. The sequence of Dz G93A is shown in Fig. 2A. Cleavage of SOD1 mRNA was carried out by incubating in vitro transcribed mRNA with Dz G93A. The cleavage by Dz G93A resulted in two discrete products from G93A SOD1 mRNA in a sequence-specific manner (Fig. 2B, left). In contrast, Dz G93A produced no detectable cleavage of wild-type target mRNA. Because of the key role of Mg^{2+} in RNA structure and in the cleavage of phosphodiester bonds, cleavage of the mutant was also assessed in the absence of $MgCl_2$ and no cleavage was observed. Next, in order to optimize the arm length to get the most effective cleavage, it was varied from 6 to 12 bases. The maximum cleavage effect was observed when the arm length was 9 bases (Fig. 2B, right). For stabilization of DNA enzyme to degradation by DNAase in cells, the two nucleotides of DNA enzymes were modified with phosphorothioate at both their 5′ and 3′ ends. This modified Dz G93A was confirmed to remain active and specific for mutant mRNA in an in vitro cleavage assay (supplement figure).

For the design of ribozyme, G93A sequence at the mutation site does not follow NUX rule, but sequences of other reported mutations at the same codon, G93R, G93S, and G93C [15], can be targeted by ribozyme. AUX triplet of G93R, G93S, and G93C is cleaved by Rz G93X, but the corresponding triplet in the wild-type, AUG, does not follow the NUX rule (Fig. 2A). The sequences of Rz G93R, G93S, and G93C are shown in Fig. 2A. In vitro cleavage reactions demonstrated that Rz G93X could convert G93R, G93S, and G93C mRNAs to the expected two cleavage products, but that wild-type mRNA was, as expected, resistant to cleavage (Fig. 2C). The optimal arm length of Rz G93X was proved to be 8 for the maximum effect (data not shown).

Rz G93X or phosphorothioate-modified Dz G93A was co-transfected with plasmids encoding each mutant SOD1 to investigate their suppression effect of protein in

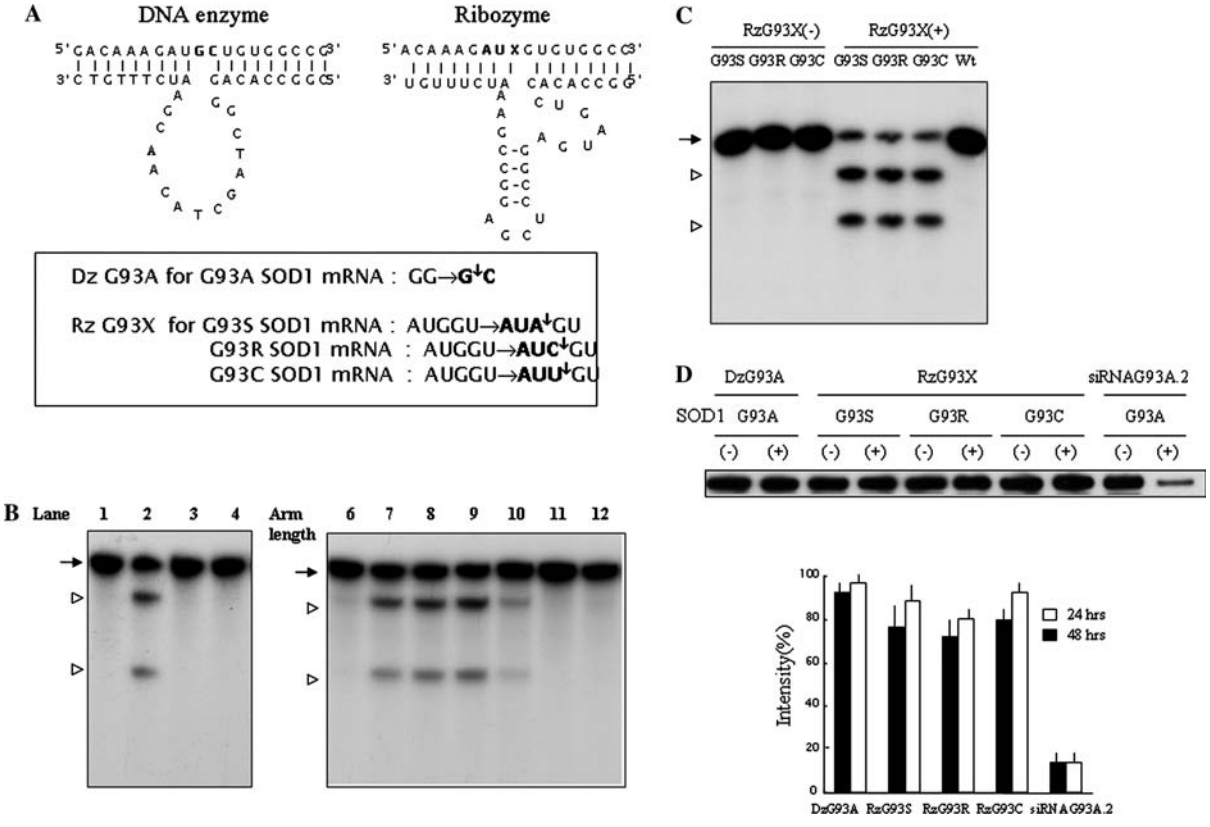

Fig. 2. DNA enzyme and ribozyme specific for mutant SOD1 at codon 93. (A) Sequences of DNA enzyme and ribozyme (upper panel) and target sequence of wild-type and mutant SOD1s. Bold characters are the target sequences. Vertical arrows indicate cleavage sites. (B) Sequence-specific (left) and arm length-dependent (right) cleavage of G93ASOD1 mRNA by Dz G93A. When [α-^{32}P]-labeled G93ASOD1 RNAs were incubated with unlabeled Dz G93A in buffer with 20 mM Mg^{2+} for 4 h, the target RNA was cleaved into two expected products in 4 h (lane 2) (lane 1, before reaction), but was not cleaved without Mg^{2+} in the reactions (lane 3). Dz G93A did not cleave wild-type SOD1 mRNA (lane 4). Cleavage by DzG93A was most effective when the arm length was nine nucleotides (right panel). Arrow, full-length SOD1 mRNA (765 nt); arrowheads, fragments (581 and 184 nt). (C) Sequence-specific cleavage of mutant SOD1 mRNAs by RzG93X in vitro. [α-^{32}P]-Labeled G93S, G93R, and G93C mRNAs were incubated with unlabeled Rz G93X for 4 h. RzG93X could cleave all three mutant mRNAs, but not wild-type mRNA. Arrow, full-length SOD1 mRNA (765 nt); arrowheads, fragments (581 and 184 nt). (D) Western blot analysis of the effect of Rz G93X, Dx G93A, and siRNA G93A on the expression of mutant SOD1 proteins in 293T cells. Blot is from 48 h after transfection. Figure shows the percentages of band intensity with Rz G93X, Dx G93A, and siRNA G93A (+) with respect to those with mock transfection (−). Values are means and SEM.

mammalian cells. The DNA enzyme at 1–10 μg had very little effect and 2 μg ribozymes suppressed expression of each mutant only to the extent of 30% in 24 h. In contrast, 2.5 nM siRNA G93A.2 (= 0.07 μg) suppressed the expression of G93A SOD1 by more than 80% as reflected in the band intensity on Western blotting both at 24 and 48 h after transfection (Fig. 2D). Thus, on a molarity comparison basis, siRNA was more effective than either ribozyme or DNA enzyme in suppressing mutant SOD1 expression.

Suppression effect of siRNA, DNA enzyme, and ribozyme for wild-type SOD1

Four siRNAs for wild-type SOD1 were designed (Fig. 3A). These siRNAs were named by the nucleotide number at the center position of each siRNA sequence towards the 5′ side of which the siRNA is presumed to cleave the substrate RNA [8,9]. siRNA396 most effectively suppressed SOD1 expression in 293T (Fig. 3B, upper) and Neuro2a cells (data not shown). In addition, this siRNA396 could suppress the expression of any mutant SOD1, such as G93A, A4V (Fig. 3B, lower), G85R or G93S (data not shown) with a similar degree of efficiency as wild-type SOD1. siRNA396 could reduce the expression of endogenous human SOD1 in 293T cells (Fig. 3C) and mouse SOD1 in N2a cells (data not shown). This reduction was most prominent at 24 h and expression returned to the normal level in 96 h.

For comparing the efficacy of siRNA, DNA enzymes, and ribozymes for wild-type SOD1, they were designed from the region between nucleotide number 382 and 419 of SOD1 ORF mRNA. The 382–419 region is presumed to be the biggest single-strand RNA region with minimal free energy (Fig. 4A, arrow), when the secondary structure of SOD1 mRNA is analyzed with the mFold program of Zuker (http://mfold.wustl.edu/~folder/rna/form1.cgi). Two siRNAs, siRNA396 and 412, three DNA enzymes, Dz394, Dz398, and Dz403, and one ribozyme, Rz405, were designed within this region (Fig. 4A). DNA enzyme and ribozyme were named by the nucleotide number on the 5′ side of the cleavage site. An in vitro cleavage assay revealed that more than 90% of the full-length mRNA was converted to the expected products by Dz394 and Rz405 after 4 h of incubation (Fig. 4B). However, in 293T and Neuro2a cells, Dz394 did not suppress the expression of SOD1 protein and Rz405 suppressed only about half of the expression. In contrast, siRNA396 suppressed the expression almost to the baseline level (Fig. 4C). As to any suppression effect on endogenous SOD1 of 293T cells, neither DNA enzyme nor ribozyme decreased the endogenous expression clearly (Fig. 4D).

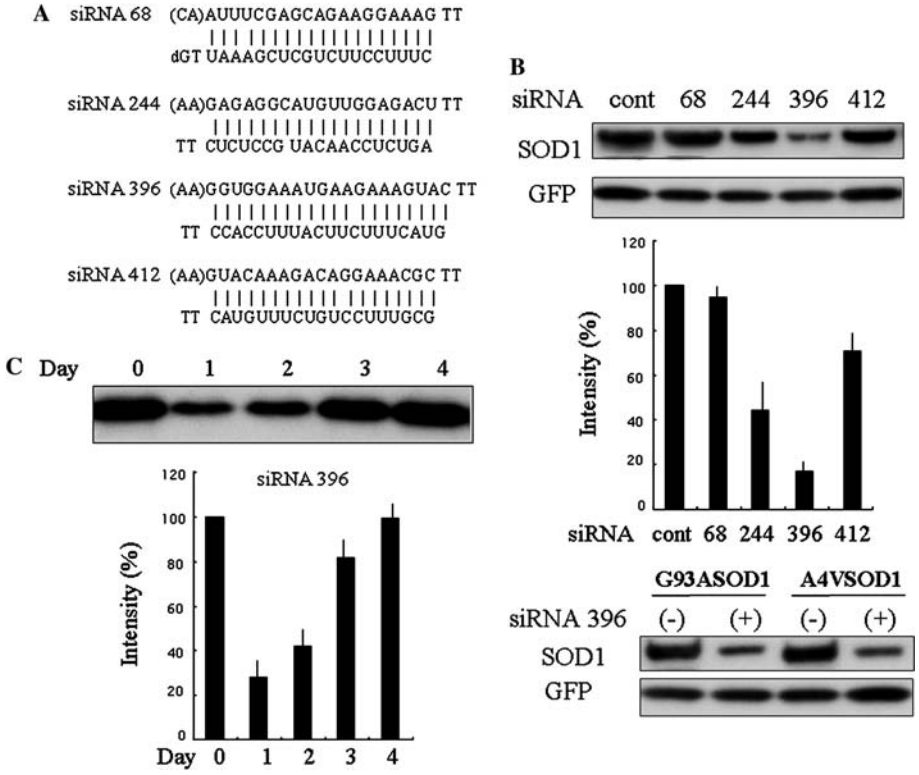

Fig. 3. siRNAs for wild-type SOD1. (A) Sequences of four siRNAs for wild-type SOD1. (B) Effect of four non-specific siRNAs on wild-type SOD1(with no tag) (upper panel) and mutant SOD1(with no tag) (lower panel) expressions in 293T cells as detected by Western blotting with anti-SOD1 antibody. Expression level of target protein was adjusted by level of co-transfected GFP expression. (C) Western blot analysis of the effect of siRNA 396 on endogenous wild-type SOD1 in 293T cells. Values are means and SEM.

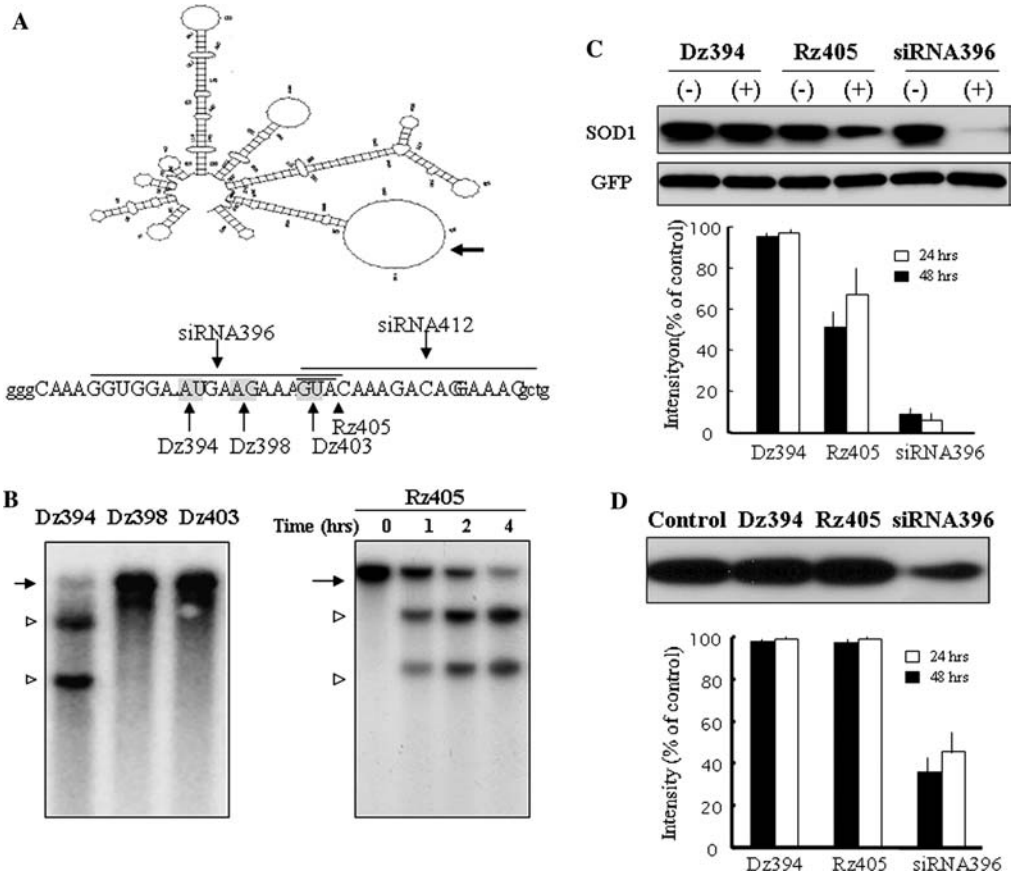

Fig. 4. DNA enzyme, ribozyme, and siRNA targeting predicted single-strand region 382–419 of wild-type SOD1 mRNA. (A) Secondary structure of the coding region of human SOD1 mRNA (upper panel). Arrow indicates the largest single-strand region (382–419) with minimal free energy. Locations of candidate cleavage site of DNA enzyme, ribozyme, and siRNA within region of 382–419 (lower panel). Upper-case letters of 382–419 sequences are included in the single-strand region and lower-case letters are in the stem region. (B) Sequence-specific cleavage of DNA enzymes (left) and Rz 405 (right). [α-^{32}P]-Labeled wild-type SOD1 RNA was incubated with DNA enzymes for 4 h. Dz 394 cleaved most of the target RNA into the two expected products, but other DNA enzymes did not (left). Arrow, full-length SOD1 mRNA (765 nt); arrowheads, fragments (446 and 319 nt). Rz 405 cleaved most of the target RNA in a time-dependent manner (right). Arrow, full-length SOD1 mRNA (765 nt); arrowheads, fragments (457 and 308 nt). (C) Effect of Dz394, Rz405, and siRNA396 on wild-type SOD1 proteins (with no tag) expressed in 293T cells as detected by Western blotting with anti-SOD1 antibody. Expression level of target protein was adjusted by level of co-transfected GFP expression. (D) Western blot analysis of the effect of siRNA 396 on endogenous wild-type SOD1 in 293T cells. Values are means and SEM.

DNA-vector based expressing siRNA

The 0.5 and 2.0 μg of DNA-vector based expressing siRNAs were co-transfected with 0.25 μg of wild-type or mutant SOD1-containing plasmids in 293T and Neuro2a cells. Both expressing siRNA vectors for G93A, siRNA V. G93A.1 and 2, significantly suppressed expression of G93ASOD1 protein, and the suppression ratios were comparable to those by siRNA G93A.1 and 2 of oligonucleotide with very little effect on wild-type SOD1 expression (Fig. 5A). There was not much difference in efficiency between 0.5 and 2.5 μg of expressing siRNAs (data not shown). The expressing siRNA vector for wild-type SOD1, siRNA V. 396, could inhibit markedly the expressions of wild-type, G93A, and A4V SOD1 proteins in similar degrees to siRNA 396 of oligonucleotide (Fig. 5B). The siRNA V. 396 suppressed the endogenous human SOD1 in 293T cells (Fig. 5C) and mouse SOD1 in N2a cells (data not shown).

Cell-toxicity assay

The suppressive effect of siRNA on mutant-SOD1-induced cell toxicity was tested using Neuro2a cells. The survival rates of mutant transformants were significantly decreased compared with wild-type transformant and vector controls in the presence of lactacystin, a proteasome inhibitor. siRNA G93A.2 increased the survival rate of G93A, but not that of A4V transformant. In contrast, siRNA396 increased the survival rates of both G93A and A4V transformants (Fig. 6). Similar effects were observed with transfection of siRNA V.G93A.2 and 396 (data not shown).

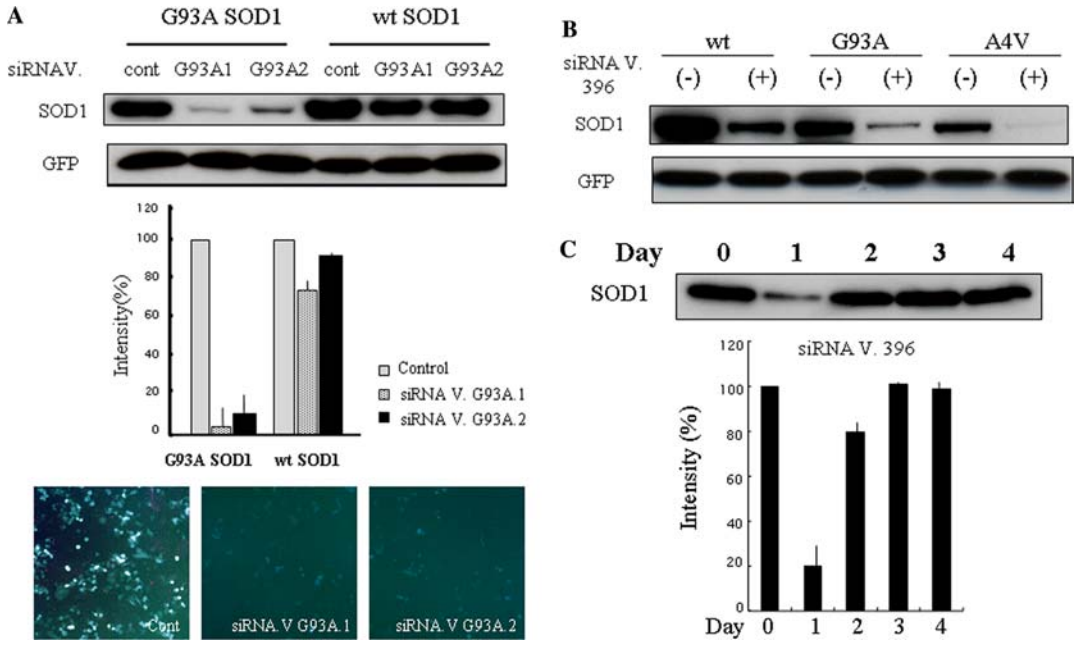

Fig. 5. Effect of DNA-vector based expressing siRNAs (siRNA V.). (A) Effect of expressing siRNA vectors for G93A SOD1 (siRNA V. G93A.1 and 2) on G93A and wild-type SOD1 protein (with no tag) expressed in Neuro2a cells as detected by Western blotting with anti-SOD1 antibody. Expression level of target protein was adjusted by level of co-transfected GFP expression (upper panel). Fluorescence of GFP-fused SODs was also suppressed by siRNA V. G93A.1 and 2 (lower panel). Expression level of target protein was adjusted by level of co-transfected DsRed fluorescence (data not shown). Data are at 48 h after transfections. Values in the figure are means and SEM. (B) Effect of expressing siRNA vectors for wild-type SOD1 (siRNA V.394) on wild-type, G93A, and A4V SOD1 protein (with no tag) expressed in 293T cells as detected by Western blotting with anti-SOD1 antibody. Expression level of target protein was adjusted by level of co-transfected GFP expression. (C) Western blot analysis of effect of siRNA V.396 on endogenous wild-type SOD1 expression in 293T cells. Values are means and SEM.

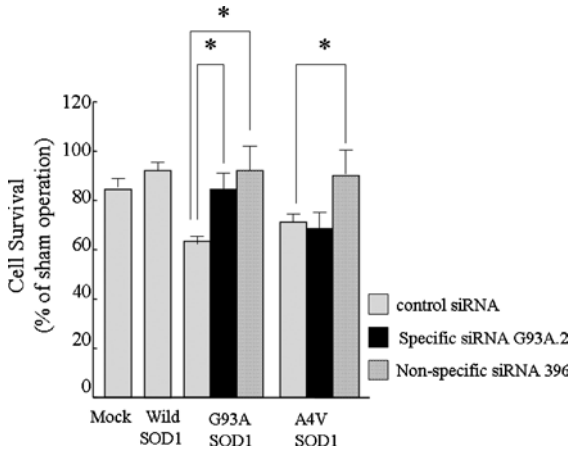

Fig. 6. siRNAs rescue the mutant SOD1-induced toxicity in mammalian cells. The relative viability of the wild-type, mutant, and mock transfectants treated with lactacystin (20 μM) compared with each without treatment of lactacystin. Lactacystin enhances the mutant SOD1-related toxicity in Neuro2a cells. siRNA G93A.2 increased the viability of G93A SOD1-transformant to the similar level of mock-transformant, but did not improve that of A4V SOD1-transformant. siRNA 396 increased the viabilities of both G93A and A4V SOD1-transformants. Values are means and SEM.

Discussion

In autosomal dominant disease, such as familial ALS, the most effective therapeutic approach requires the reduction of the aberrant mutant protein leaving wild-type protein intact. Possible candidate methods include ribozyme, DNA enzyme, and siRNA to cleave mutant RNA selectively. Antisense RNA or DNA has been used to reduce the expression of target protein, but these do not discriminate between the wild-type and mutant mRNA of SOD1, most of which has a point mutation [15]. siRNA G93A.1 and 2, which were designed to target the G93A mutant specifically, suppressed the expression of approximately 90% of G93A SOD1 protein, a suppression rate that is similar to that described in the original report on siRNA [5]. In contrast, they had much less effect on the expression of wild-type SOD1 and especially siRNA G93A.2 had close to no effect on wild-type SOD1 expression. While nucleotides in the 3′- and 5′- terminal region (except for the 3′ overhang of the siRNA sequence) do not contribute to the specificity of target recognition, nucleotides in the center of the siRNA sequence are important specificity determinants [5,16]. That the mutation site in siRNA G93A.2 is located more in the center of the sequence than that in siRNA G93A.1 might explain the lesser effect of G93A.2 on wild-type SOD1 compared to G93A.1.

Ribozymes and DNA enzymes also can discriminate even a single nucleotide mismatch. In our experiments the ribozyme and DNA enzyme, designed for SOD1 mutants at codon 93, were absolutely specific for the mutant

sequence, as shown by in vitro cleavage reactions. However, in contrast to the specificity, suppression of mutant SOD1 protein expression by them in the mammalian cells was much lower than that obtained with siRNA G93A under the conditions used in our investigation.

Two possible explanations may account for such a big difference in efficiency between siRNA and DNA enzyme/ribozyme at codon 93. First, double-stranded siRNAs are protected by proteins in cells from attacks by ribonucleases, whereas single-stranded RNA/DNA are not, as demonstrated earlier [11]. Second, the secondary structure of SOD1 mRNA at this site might not be accessible by ribozyme or DNA enzyme. The secondary structure of target RNA highly influences the efficiencies of ribozyme and DNA enzyme, but not that of siRNA [4,5,16], probably because, in some step of siRNA, ATP-dependent RNA helicase may unwind duplex RNA [9,17]. Therefore, we also compared the ribozyme, DNA enzyme, and siRNA that were designed to target the largest single-strand region of SOD1 ORF mRNA with minimal free energy predicted by the mFold program of Zuker. Actually, Rz405 and Dz398 cleaved most of the in vitro-transcribed full-length SOD1 RNA in 4 h, with efficiencies that were much better than those for Rz G93X and Dz G93A, and were comparable to or even better than those of reported constructs [18,19]. For the ribozyme expression in the cells, furthermore, an internally cleaved hairpin ribozyme cassette was inserted downstream of the hammerhead ribozyme to remove 3′ extraneous sequences, which may interfere with ribozyme activity [13,20]. Rz405, as well as Dz398 was, however, still much less efficient in the cells than siRNA396.

It is a very important result for the gene therapy of congenital disease that siRNA396 could efficiently suppress endogenous SOD1 expression. Considering the facts that the half-life of SOD1 protein is a few days and that transfection efficiency of siRNA was 80–90% (judging by the result of the control GFP plasmid), a 60–70% reduction of total endogenous SOD1 by siRNA396 (Fig. 3C) suggests nearly complete elimination of endogenous SOD1 expression in the successfully transfected cells. In contrast, neither Rz405 nor Dz398 was effective in suppressing endogenous SOD1 expression. Therefore, the current studies would suggest that siRNA is clearly a potent and promising tool for silencing of the target gene in cells.

Although our non-specific siRNAs do not discriminate between mutant and wild-type SOD1 mRNAs, it is possible that a reduction in expression of both mutant and wild-type SOD1 may also be beneficial for rescue of the phenotype. There are several lines of evidences suggesting that reduction of wild-type SOD1 activity will not produce or enhance the phenotype of motor neuron loss. First, in ALS patients with SOD1 mutations neither the age of onset nor the rapidity of progression of disease correlates with SOD1 activity level [15]. Although the downregulation of SOD1 may cause neuronal death in cultured cells [21], SOD1 null mice developed normally without motor neuron disease [22]. More importantly, elimination of wild-type endogenous SOD1 by crossing G85R SOD1 transgenic mice with SOD1 null mice was found to have no effect on mutant-mediated disease [23]. These observations suggest the possibility that reduction of mutant proteins, even if it is accompanied by the reduction of wild-type SOD1 to a similar degree, may be sufficient for improving the phenotype. In our cell line model, indeed, siRNA396, which suppressed expression of both mutant and wild-type SOD1, rescued the enhanced cell toxicity produced by overexpression of G93A and A4V SOD1s.

For the application of the siRNA approach to gene therapy of neurodegenerative disease in vivo, we must develop a way to achieve long-term expression of siRNA in post-mitotic neurons (and possibly glia, as well). siRNA therapy, like antisense DNA and DNA enzyme therapies, requires continuous delivery of sufficient quantities of therapeutic molecules to inhibit translation of target mRNA. In contrast, ribozyme encoded in recombinant adeno-associated viruses (rAAVs) can be incorporated in the host chromosomal DNA in neurons and transcribed indefinitely [24]. Therefore, in order to use a viral delivery system for siRNA, we tried vector-mediated expression of siRNA. We constructed a DNA-based siRNA expression vector in which each sense and antisense siRNA sequence was placed under control of human U6 promoter with a termination signal at the 3′ end (short stretch of uridines). Expressed stem-loop transcript would be cleaved by endogenous Dicer and form siRNA duplexes with two 3′ overhangs in the cells. All of the expressing vectors of siRNA G93A.1, G93A.2, and 396 worked well, i.e., to the similar degree to siRNA of oligonucleotides in cells. We are in the process of making rAAV and transgenic mice expressing siRNA396 and G93A.2 for investigating the efficacy of siRNAs in vivo. Although a less-invasive delivery method for introducing in vivo cells is needed for clinical feasibility, the efficiency of our siRNA and expressing RNA vector to reduce mutant SOD1 protein in cells suggests that this mRNA-targeting approach by siRNA might provide effective therapy for autosomal dominant disease, such as familial ALS.

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