

Site-specific Inhibitory Mechanism for Amyloid- β 42 Aggregation by Catechol-Type Flavonoids Targeting the Lys Residues*

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Background: The inhibitory mechanism of A β 42 aggregation by flavonoid is fully unknown.

Results: The oxidant enhanced the inhibitory activity of (+)-taxifolin against A β 42 aggregation by forming A β 42-taxifolin adducts between the Lys-residues and oxidized (+)-taxifolin.

Conclusion: The inhibitory activity of catechol-type flavonoids requires auto-oxidation to form an *o*-quinone to react with Lys.

Significance: These may help design promising inhibitors against A β 42 aggregation for Alzheimer's therapy. (60<60 words)

SUMMARY (239<250 words)

The aggregation of 42-residue amyloid β -protein (A β 42) is involved in the pathogenesis of Alzheimer's disease (AD). Numerous flavonoids exhibit inhibitory activity against A β 42 aggregation, but their mechanism remains unclear in molecular level. Here we propose the site-specific inhibitory mechanism of (+)-taxifolin, a catechol-type flavonoid, whose 3',4'-dihydroxyl groups of the B-ring plays a critical role. Addition of sodium periodate, an oxidant, strengthened suppression of A β 42 aggregation by (+)-taxifolin, whereas no inhibition was observed under anaerobic conditions, suggesting the inhibition to be associated with

the oxidation to form *o*-quinone. Since the formation of A β 42-taxifolin adduct was suggested by mass spectrometry, A β 42 mutants substituted at Arg5, Lys16, and/or Lys28 with norleucine (*nL*) were prepared to identify the residues involved in the conjugate formation. (+)-Taxifolin did not suppress the aggregation of A β 42 mutants at Lys16 and/or Lys28 except for the mutant at Arg5. In addition, the aggregation of A β 42 was inhibited by other catechol-type flavonoids, while that of K16*nL*-A β 42 was not. In contrast, some non-catechol-type flavonoids suppressed the aggregation of K16*nL*-A β 42 as well as A β 42. Furthermore, interaction of (+)-taxifolin with β -sheet region in A β 42 was not observed using solid-state NMR unlike curcumin of non-catechol-type. These results demonstrate that catechol-type flavonoids could specifically suppress A β 42 aggregation by targeting Lys-residues. Although the anti-AD activity of flavonoids has been ascribed to their anti-oxidative activity, the mechanism that the *o*-quinone reacts with Lys-residues of A β 42 might be more intrinsic. The Lys-residues could be targets for Alzheimer's therapy.

Alzheimer's disease (AD) is characterized by amyloid deposition in senile plaques mainly consisting of 40- and 42-mer amyloid β -proteins (A β 40, A β 42) (1,2). These proteins are generated from the amyloid precursor protein by β - and γ -secretases (amyloidogenic pathway). A β aggregates mainly through intermolecular β -sheet formation and shows neurotoxicity *in vitro* (3). A β 42 plays a more pivotal role in the pathogenesis of AD than A β 40 because of its higher aggregative ability and neurotoxicity (3). It has been well documented that soluble A β oligomeric assemblies rather than insoluble fibrils cause memory loss and neuronal death (4,5). Oxidative stress is one of the major contributing factors to neurodegenerative disease progression (6). A β -induced toxicity has been correlated to oxidative damage through protein radicalization *in vitro* (7,8) and *in vivo* (9,10).

Researchers have reported protective effects of various polyphenols from green tea, turmeric, and red wine *etc.*, against A β aggregation and neurotoxicity (11-13). Several compounds [e.g. (-)-epigallocatechin-3-gallate (EGCG), curcumin, and resveratorol] are in clinical or preclinical trials for AD treatment (14,15). However, the recent failures of some trials (16) motivated us to clarify the mechanism by which polyphenols inhibit the aggregation of A β 42 to develop promising leads for clinical use.

Concerning the molecular interaction of A β with flavonoids, a docking simulation by Keshet *et al.* predicted the involvement of Lys28 and the C-terminal region in the binding with myricetin (17). However, the precise mode of binding with flavonoids has scarcely been addressed, except for limited studies using NMR spectroscopy [curcumin (18), EGCG (19), and myricetin (20)], which suggested less-specific interaction with the β -sheet region in A β .

Our group recently found that silymarin, seed extracts of *Silybum marianum*, attenuated AD-like pathologic features, such as senile plaques, neuroinflammation, behavioral dysfunction, and A β oligomer formation using a well-established AD mouse model (J20) (21). We also isolated (+)-taxifolin (22), a flavanonol which has a catechol moiety on the B-ring (Fig. 1A), as a

component of the extracts that prevents A β 42 aggregation (23). "Aggregation" used in this paper means the process of A β 42 monomer to form fibrils by way of oligomer and/or protofibril. This paper describes a comprehensive study on the ability of (+)-taxifolin to prevent aggregation and β -sheet formation of A β 42, along with the effects of various flavanonols and flavonols on the aggregation of A β 42 mutants substituted at Arg5, Lys16, and/or Lys28 with norleucine (*nL*). These results together with the results of liquid chromatography-mass spectrometry (LC-MS) led us to propose a site-specific inhibitory mechanism for A β 42 aggregation by catechol-type flavonoids, where adduct formation at the Lys-residues in A β 42 with the *o*-quinone derived from flavonoids could be involved in the suppression of A β 42 aggregation.

EXPERIMENTAL PROCEDURES

Synthesis of (+)-Taxifolin, Dihydrokaempferol and Pinobanksin— A naturally-occurring form of (+)-taxifolin was synthesized (Scheme S1A in Supplemental Data) basically according to the previous reports (23,24). Briefly, vanillin was demethylated by treatment with boron tribromide to give 3,4-dihydroxybenzaldehyde quantitatively, whose phenolic hydroxyl groups were protected with methoxymethyl groups. The phenolic hydroxyl groups of 2,4,6-trihydroxyacetophenone were also protected with methoxymethyl groups. A cross-aldol reaction between these products, followed by treatment with H₂O₂ under a basic condition, yielded the epoxide **7** (supplemental Scheme S1A), which was cyclized and deprotected under an acidic condition to give (\pm)-taxifolin. (+)-Taxifolin was separated by HPLC on a CHIRALCEL OJ-RH column (10 mm i.d. x 150 mm; Daicel Corporation, Osaka, Japan) using 15% CH₃CN/H₂O containing 0.1 % acetic acid (25). Synthesis of ¹³C₆(+)-taxifolin was performed by using vanillin-ring-¹³C₆ (Isotec, Miamisburg, OH) as a starting material.

(\pm)-Dihydrokaempferol (**26**) and (\pm)-pinobanksin (**27**) were synthesized in a manner similar to (\pm)-taxifolin using 4-hydroxybenzaldehyde or benzaldehyde in place of vanillin as a starting material, respectively

(supplemental Scheme S1A). Enantiomers were not separated because the inhibitory effect on A β 42 aggregation by (-)-taxifolin was almost the same as that by (+)-taxifolin (23). The structure of each of these compounds was confirmed by ¹H NMR (AVANCE III 500, ref. TMS, Bruker, Germany) and EI-MS (JMS-600H, JEOL, Tokyo, Japan). EI-MS data were as follows: (+)-taxifolin (*m/z* 304 [M]⁺), ¹³C₆-(+)-taxifolin (*m/z* 310 [M]⁺), dihydrokaempferol (*m/z* 288 [M]⁺), and pinobanksin (*m/z* 272 [M]⁺). The spectra of ¹H NMR (28) and ¹³C NMR (29) of ¹³C₆-(+)-taxifolin are shown in supplemental Fig. S1. The optical rotation of each enantiomer was; (+)-taxifolin [α]_D +17.3 (*c* 0.1, MeOH), (-)-taxifolin [α]_D -16.2 (*c* 0.1, MeOH), almost equal to those reported previously; (+)-taxifolin [α]_D +19.0 (*c* 0.1, MeOH) (22). Other flavonoids; myricetin (Wako, Osaka, Japan), kaempferol, (\pm)-dihydromyricetin (ChromaDex, Irvine, CA), morin, galangin, quercetin (Sigma, St. Louis, MO), and datiscetin (Extrasynthese, Genay, France) were purchased commercially.

Trapping of the o-Quinone Form of (+)-Taxifolin by Phenylenediamine—Sodium periodate (NaIO₄, 19 mg, 89 μ mol) in H₂O (0.20 mL) was added to (\pm)-taxifolin (28 mg, 91 μ mol; Toronto Research Chemicals Inc. North York, ON, Canada) in methanol (3.5 mL). After stirring for 15 min at room temperature, the reaction mixture was extracted with ethyl acetate (5.0 mL), to which 1,2-phenylenediamine (9.8 mg, 91 μ mol; Wako) was added before stirring for 30 min at room temperature. The mixture was concentrated and separated by HPLC on a YMC SH-342-5AL column (20 mm i.d. x 150 mm; YMC, Kyoto, Japan) with 60% MeOH/H₂O to give the corresponding phenazine (3.8%) (supplemental Scheme S1B). The structure was confirmed by ¹H NMR and high resolution (HR)-EI-MS. ¹H NMR (500 MHz, 295.3 K, acetone-*d*₆, 6.98 mM) δ 4.87 (1H, d, *J* = 11.5 Hz), 5.59 (1H, d, *J* = 11.5 Hz), 6.07 (1H, s), 6.09 (1H, s), 7.96-8.00 (2H, m), 8.22 (1H, dd, *J* = 9.0, 1.7 Hz), 8.26-8.30 (2H, m), 8.33 (1H, d, *J* = 9.0 Hz), 8.46 (1H, d, *J* = 1.7 Hz), 11.72 (1H, brs); HR-EI-MS *m/z* 374.0902 [M]⁺, calcd for C₂₁H₁₄N₂O₅ 374.0903.

Thioflavin-T Fluorescence Assay—The aggregative ability of A β 42 was evaluated at 37 °C by the thioflavin-T (Th-T) method developed by Naiki *et al* (30). The procedure was described elsewhere (31). Fluorescence intensity was measured at 420 nm excitation and 485 nm emission using a micro-plate reader (MPR-A4uII; TOSOH, Tokyo, Japan, or Fluoroskan Ascent; Thermo Scientific, Rockford, IL). In brief, A β 42 was dissolved in 0.1% NH₄OH at 250 μ M, and each flavonoid was dissolved in EtOH at 5 mM, followed by dilution with sodium phosphate-buffered saline (PBS: 50 mM sodium phosphate and 100 mM NaCl, pH 7.4) at the desired concentration (A β 42, 25 μ M; flavonoids, 50 μ M). NaIO₄ or Tris(2-carboxyethyl)phosphine hydrochloride (TCEP-HCl) was initially dissolved in PBS at 100 mM, then diluted with PBS at 100 μ M before use. Experiments under an anaerobic condition were performed in a desiccator evacuated by a diaphragm pump (*ca.* 8 mmHg; KNF Lab LABOPORT vacuum pump, KNF Neuberger, NJ) at room temperature. Unless otherwise noted, the concentrations of A β 42, flavonoids, and oxidant/reductant used in this study were 25, 50, and 100 μ M, respectively.

The effect of the addition of NaIO₄ on Met35 oxidation was estimated by HPLC on a Develosil ODS UG-5 column (6.0 mm i.d. x 100 mm; Nomura chemical, Seto, Japan) under a gradient of 10-50% CH₃CN containing 0.1% NH₄OH for 40 min after the centrifugation of the A β 42 solution at 20,130 g at 4 °C (MX-300; TOMY, Tokyo, Japan) for 10 min.

The seeds of A β 42 were also prepared basically according to the protocol developed by Naiki *et al* (30). Briefly, after incubation of A β 42 (25 μ M) in PBS (pH 7.4) for 24 h at 37 °C, the pellet obtained by centrifugation at 20,130 g at 4 °C for 1 h was suspended by pipetting in PBS (pH 7.4) at concentration of 1 mg/mL. The resultant solution was sonicated for 1 h in an ultrasonic device (MUS-20; EYELA, Tokyo, Japan), followed by dilution with PBS at 10 μ g/mL before use. Th-T relative fluorescence was expressed as a percentage of wild-type A β 42

alone, whose maximum value was taken as 100%.

Transmission Electron Microscopy (TEM)—The aggregates of A β 42 after a 48-h incubation were examined under a H-7650 electron microscope (Hitachi, Ibaraki, Japan). The experimental procedure was described elsewhere (31).

UV-visible Spectrometry—Oxidation of (+)-taxifolin was monitored by UV spectroscopy (UV-2200A; Shimadzu, Kyoto, Japan). (+)-Taxifolin (50 μ M) was incubated with A β 42 (25 μ M) in PBS (50 mM sodium phosphate and 100 mM NaCl, pH 7.4) at 37 °C. The solution was then loaded into a 1-cm path length quartz cell, and UV spectra were recorded at 200-500 nm. The sample was diluted three times with PBS because of its strong absorbance.

Circular Dichroism (CD) Spectrometry—The secondary structure of A β 42 was estimated by CD spectrometry (J-805; JASCO, Tokyo, Japan) using a 0.1-mm quartz cell (121.027-QS, ϕ 10 mm; JASCO), as described elsewhere (32). A β 42 (25 μ M) was incubated with or without (+)-taxifolin (50 μ M) in PBS (50 mM sodium phosphate and 100 mM NaCl, pH 7.4) at 37 °C. An aliquot was loaded into the quartz cell, and CD spectra were recorded at 190-250 nm. Experiments under an anaerobic condition were performed as described before. The spectra of A β 42 mutants are shown after subtraction of the spectrum for vehicle alone, and those in the presence of (+)-taxifolin are shown after subtraction of the spectrum for (+)-taxifolin alone.

LC-MS Analysis—A β 42 solution (25 μ M) was incubated with 50 μ M (+)-taxifolin in PBS (50 mM sodium phosphate and 100 mM NaCl, pH 7.4) in the presence of 100 μ M NaIO₄ at 37 °C. After a 4-h incubation, the mixture was desalted and condensed twice by ZipTip C18 (Millipore, Bedford, MA). Five microliters of the solution was subjected to a liquid chromatography mass spectrometry ion trap time-of-flight (LCMS-IT-TOF; Shimadzu) through a

YMC-Pack ODS-AQ column (6.0 mm i.d. x 100 mm; YMC) at 25 °C under a gradient of 20-60% CH₃CN containing 0.1% formic acid for 30 min.

Synthesis of A β 42 Mutants—Fmoc-norleucine (*n*L)-OH was purchased from Watanabe Chemical Industries (Hiroshima, Japan). L-Alanine (¹³C₃, ¹⁵N), L-phenylalanine (¹³C₆), and L-valine (¹³C₅, ¹⁵N) were purchased from Isotec, and L-lysine (¹³C₆, ¹⁵N₂) and L-serine (¹³C₃, ¹⁵N) from Cambridge Isotope Laboratories (Frontage Road Andover, MA). Each labeled amino acid was protected by an Fmoc group as previously reported (33,34). The structure of each Fmoc derivative was confirmed by ¹H NMR, ¹³C NMR, and FAB-MS.

The A β 42 mutants were synthesized in a stepwise fashion on 0.1 mmol of preloaded Fmoc-L-Ala-PEG-PS resin using a PioneerTM Peptide Synthesizer (Applied Biosystems, Foster City, CA) as reported previously (35). After the chain elongation was completed, the peptide-resin was treated with a cocktail containing trifluoroacetic acid, *m*-cresol, thioanisole, and 1,2-ethanedithiol for final deprotection and cleavage from the resin. The crude peptide was precipitated by diethylether and purified by HPLC under an alkaline condition as described previously (31). After lyophilization, we obtained the corresponding pure A β 42 peptide, the purity of which was confirmed by HPLC (>98%). The molecular weight of each A β 42 mutant was confirmed by matrix-assisted laser desorption/ionization time-of-flight mass spectrometry (MALDI-TOF-MS, AXIMA-CFR; Shimadzu); R5*n*L-A β 42 (*m/z*, calcd: 4472.11, found: 4472.38 [M+H]⁺), K16*n*L-A β 42 (*m/z*, calcd: 4500.12, found: 4500.25 [M+H]⁺), K28*n*L-A β 42 (*m/z*, calcd: 4500.12, found: 4500.32 [M+H]⁺), K16,K28(*n*L)₂-A β 42 (*m/z*, calcd: 4485.11, found: 4485.13 [M+H]⁺), R5,K16,K28(*n*L)₃-A β 42 (*m/z*, calcd: 4442.08, found: 4442.58 [M+H]⁺), ¹³C,¹⁵N labeled-A β 42 (*m/z*, calcd: 4538.90, found: 4538.94 [M+H]⁺).

Solid-state NMR Analysis—A β 42 was labeled at Ala2 (¹³C₃, ¹⁵N), Ser8 (¹³C₃, ¹⁵N), Lys16 (¹³C₆, ¹⁵N₂), Val18 (¹³C₅, ¹⁵N), Phe19, and Phe20 (¹³C₆).

(+)-Taxifolin was labeled with $^{13}\text{C}_6$ on the B-ring as mentioned above (23,24). The labeled A β 42 (13 μM) was incubated with $^{13}\text{C}_6$ -(+)-taxifolin (145 μM) in PBS (50 mM sodium phosphate and 100 mM NaCl, pH 7.4) at 37 $^\circ\text{C}$. After 48 h of incubation, the solution was centrifuged (27,720 g, PRP-20-2; Hitachi) for 15 min at 4 $^\circ\text{C}$, and then the precipitate was dried *in vacuo* to give the labeled A β 42 aggregate associated with $^{13}\text{C}_6$ -(+)-taxifolin (12 mg). The solid-state NMR experiments were performed at 14 T (600 MHz for ^1H) using a JEOL ECA-600 spectrometer and a custom-fabricated probe with a Chemagnetics 3.2 mm spinning system at a magic angle spinning (MAS) frequency of 21 kHz at room temperature as reported previously (18). The ^{13}C chemical shifts were calibrated in ppm relative to tetramethylsilane by considering the ^{13}C chemical shift for methine ^{13}C of solid adamantane (29.5 ppm) as an external reference. The ^{13}C chemical shifts of labeled A β 42 and (+)-taxifolin were assigned according to 1D- ^{13}C CP/MAS NMR spectra (supplemental Fig. S2A). For the broadband ^{13}C - ^{13}C correlation 2D experiments, dipolar-assisted rotational resonance (DARR) was used (36). Pulse sequence parameters of the NMR experiment were as follows; two pulse phase-modulated (TPPM) ^1H decoupling power = 80 kHz, RAMP-CP contact time = 1.2 ms, pulse delay = 2 s, t_1 increment = 23.7 μs , t_1 points of 2D = 128 pt, and mixing time (τm) = 50 ms or 500 ms. The window function 'HAMMING' was used in all 2D FT spectra to minimize t_1 noise. As the 2D FT DARR spectra were difficult to analyze because of the t_1 noise (supplemental Fig. S2C), we applied covariance data processing to obtain a better representation of the 2D spectrum (supplemental Fig. S2B). After Fourier transformation along the t_2 dimension and phase correction, the resulting data matrix was used for covariance processing as previously reported (18,37). The covariance processing step was accelerated by singular value decomposition (38).

Statistical Analyses—All data are presented as the means \pm s.e.m. and the differences were analyzed with an one-way analysis of variance (ANOVA) followed by Bonferroni's test or unpaired Student's *t*-test. These tests were

implemented within GraphPad Prism software (version 5.0d). *P* values < 0.05 were considered significant.

RESULTS

Effects of Auto-oxidation of (+)-Taxifolin on Its Ability to Prevent the Aggregation of A β 42—We recently revealed that a catechol moiety on the B-ring of (+)-taxifolin (Fig. 1A) played important role on the inhibitory activity against A β 42 aggregation (23). A catechol moiety is easily oxidized to form an *o*-quinone (39). To investigate the contribution of auto-oxidation to the inhibitory ability, we examined the aggregative ability of A β 42 in the presence of (+)-taxifolin treated with sodium periodate (NaIO_4), which is known as an oxidant of catechol (40). As shown in Fig. 1B, NaIO_4 extensively promoted the suppressive ability of (+)-taxifolin compared with (+)-taxifolin alone. These observations were also confirmed by the TEM experiment (Fig. 2A). NaIO_4 treatment in the presence of (+)-taxifolin formed only shorter and thinner fibrils compared with (+)-taxifolin alone. A β 42 formed the typical fibrils even in the presence of NaIO_4 alone, and almost no differences (*e.g.* length, thickness) were observed between the morphology in the presence and absence of NaIO_4 (Fig 2A).

NaIO_4 alone slightly affected the Th-T fluorescence of A β 42 aggregates (Fig. 1B) possibly because NaIO_4 can oxidize Met35 in A β 42 to its sulfoxide, the formation of which was confirmed by HPLC (Fig. 1D) and MALDI-TOF-MS (A β 42-M35^{ox}; *m/z*: calcd: 4531.14, found: 4531.55 [$\text{M}+\text{H}$]⁺). This is in good agreement with a report that oxidation using hydrogen peroxide, a strong oxidant, reduced A β 42 aggregation (41). However, in the presence of both (+)-taxifolin (50 μM) and NaIO_4 (100 μM), Met35 was not oxidized by NaIO_4 ; this was confirmed by HPLC (Fig. 1D) and MALDI-TOF-MS (A β 42-M35^{red}; *m/z*: calcd: 4515.14, found: 4516.26 [$\text{M}+\text{H}$]⁺). This indicates that NaIO_4 preferred to oxidize (+)-taxifolin more than the sulfur atom of the Met35 of A β 42.

In addition, we tested whether the treatment of NaIO₄ leads to the oxidation of Met35 in the preformed Aβ42 fibrils. The fibrils (*ca.* 28 μg) treated with NaIO₄ for 4 h were dissolved in formic acid (10 μL), and were sonicated for 1 h. After volatilization, the resultant pellets were resolved in 50% acetonitrile containing 0.1% trifluoroacetic acid, followed by subjection to MALDI-TOF-MS analysis. NaIO₄ did not oxidize Met35 in the preformed Aβ42 fibril (Aβ42-M35^{red}; *m/z*: calcd: 4515.14, found: 4515.12 [M+H]⁺). Also in Th-T assay, Aβ42 fibril was not disassembled by NaIO₄ (data not shown). These mean that NaIO₄ could partially oxidize Met35 in the monomeric Aβ42, but not the fibrils.

In order to investigate the role of oxygen, suppression of Aβ42 aggregation by (+)-taxifolin was tested *in vacuo*. Notably, (+)-taxifolin little suppressed the aggregation of Aβ42 under an anaerobic condition (Fig. 1C). In TEM images, typical fibril formation was observed even in the presence of (+)-taxifolin under the anaerobic condition (Fig. 2A). Furthermore, Aβ42 aggregated in the presence of (+)-taxifolin and tris(2-carboxyethyl)phosphine (TCEP), a reductant (Fig. 1E). These results suggest the auto-oxidation of (+)-taxifolin to be required for inhibitory activity against Aβ42 aggregation.

The mechanism of Aβ42 fibril formation is well explained by a nucleation-dependent polymerization model mainly consisted of nucleation phase and extension phase (42,43). To determine which stage (nucleation phase or extension phase) was affected by (+)-taxifolin, we examined the effect of (+)-taxifolin on Aβ42 aggregation in the presence of the fibril seed as a template, according to the protocol developed by Naiki *et al.* (30). As shown in Fig 1F, there was a nucleation phase (~1 h) when Aβ42 was incubated alone, whereas addition of the seeds skipped the nucleation phase, resulting in the rapid formation of Aβ42 fibrils. In the case of co-incubation of (+)-taxifolin with the seeds, the nucleation phase of Aβ42 did not drastically change, but the fluorescence gradually decreased after incubation for 4 h, suggesting that (+)-taxifolin could prevent the elongation phase

(~2 or 4 h) in Aβ42 aggregation, rather than the nucleation phase (~1 h) (Fig. 1B, F). Although the slight difference of the length of elongation phase between Fig. 1B and 1F might be deduced from several factors, for example, outside temperature, batch (lot) of Aβ42, 2~4 h as an averaged time for elongation phase were observed in another independent experiments. Moreover, we have recently reported the ability of (+)-taxifolin to destabilize the preformed Aβ42 fibril (23). The disappearance of nucleation phase in the presence of seed and NaIO₄ (Fig. 1F) implied the ability of oxidized taxifolin to disassemble even the seed. Indeed, the fluorescence of preformed Aβ42 fibrils immediately disappeared after addition of (+)-taxifolin treated with NaIO₄ (data not shown).

Next, we measured UV spectra of (+)-taxifolin incubated with Aβ42 to evaluate the effects of NaIO₄ or the anaerobic condition on the auto-oxidation of (+)-taxifolin. When Aβ42 was incubated with (+)-taxifolin under air, the intensity of the peak at 260 nm and 400 nm gradually increased, and that of the peak at 320 nm decreased during 48 h of incubation (Fig. 2B). These spectral changes are characteristic of the oxidation of catechol-type flavonoids to form the *o*-quinone structure (44). The addition of NaIO₄ accelerated these UV changes (Fig. 2B). In contrast, there was almost no change in the UV spectra when (+)-taxifolin and Aβ42 were co-incubated *in vacuo* or with TCEP (Fig. 2B). These results indicate that the *o*-quinone formation in (+)-taxifolin through auto-oxidation plays a critical role in the inhibition of Aβ42 aggregation. The UV spectra of Aβ42 alone remained almost constant during the incubation (data not shown), meaning that the spectra of Aβ42 itself did not affect those of (+)-taxifolin.

Conversion to the *o*-quinone from (±)-taxifolin in the presence of NaIO₄ was also verified by reacting with *o*-phenylenediamine to yield phenazine (supplemental Scheme S1B), whose structure was confirmed by ¹H NMR and HR-EI-MS.

Effects of Auto-oxidation of (+)-Taxifolin on Its Ability to Inhibit Transformation of a Random

Structure into a β -Sheet in A β 42—We investigated the effects of auto-oxidation of (+)-taxifolin on the secondary structure of A β 42 by using CD spectroscopy. Shown in Fig. 3A is the data for A β 42; the positive peak at 195 nm and negative peak at 215 nm drastically increased even after 4 h of incubation, and remained until 48 h of incubation, suggesting that a random structure transformed into a β -sheet in A β 42. On the other hand, (+)-taxifolin strongly delayed the transformation of A β 42 (Fig. 3B). Furthermore, addition of NaIO₄ decelerated the transformation process during 0~8 h (Fig. 3C).

We also measured the CD spectra under an anaerobic condition (Fig. 3D, E). A spectrum related to the β -sheet formation was found only after 24 h of incubation, but its peak intensity was weaker than that of A β 42 under air in Fig. 3A. Since radicalization of A β 42 induced by reactive oxygen species is indispensable to its aggregation (8), these results seem to be reasonable. The transformation into a β -sheet was not suppressed either by (+)-taxifolin *in vacuo*. The findings suggest that the effects of auto-oxidation of (+)-taxifolin on its ability to inhibit A β 42 aggregation are closely associated with prevention of the transformation into a β -sheet.

LC-MS Analysis of A β 42 Treated with Oxidized Taxifolin—The *o*-quinone of flavonoids can form covalent bonds with nucleophilic residues in proteins (e.g. Cys, Arg, Lys) to modulate their activity (39,45). Because A β 42 has three basic amino acid residues (Arg5, Lys16, Lys28), we asked if these residues bound to oxidized taxifolin covalently. The *o*-quinone derived from (+)-taxifolin can react with Lys or Arg residues in A β 42 through a Michael addition or Schiff base formation (Fig. 4A). We analyzed an A β 42 solution incubated with (+)-taxifolin and NaIO₄ for 4 h using a highly sensitive ion trap type LC-MS equipped with a TOF mass analyzer (LCMS-IT-TOF). As shown in Fig. 4B, LC-MS measurements gave the mass envelop at +7, +6, and +5 charge distribution (deconvoluted mass: 4817.12, calcd: 4816.38), corresponding to the A β 42-oxidized taxifolin adduct resulted from Michael addition. These results imply that the

basic amino acid residues of A β 42 might be involved in the covalent bonding with the oxidized taxifolin.

Inhibitory Effect of (+)-Taxifolin on Aggregation of A β 42 Mutants Substituted at Arg5, Lys16, and/or Lys28—Although formation of Michael adducts between the *o*-quinone of (+)-taxifolin and the Lys residues of A β 42 was suggested in LC-MS (Fig. 4B) together with the verification of the *o*-quinone formation (supplemental Scheme S1B), an attempt to determine the Lys residues involved in the adduct formation by LC-MS-MS analysis was disappointing, possibly because of the extremely low amount and/or instability of the adduct. To obtain further insight into the mechanism by which (+)-taxifolin inhibits the aggregation of A β 42, we prepared five A β 42 mutants [R5nL-, K16nL-, K28nL-, K16,K28(nL)₂-, and R5,K16,K28(nL)₃-A β 42], where the basic amino acid residues of A β 42 were substituted with norleucine (nL). The aggregative ability in the presence or absence of (+)-taxifolin was also estimated (Figs. 5A-E). These mutants retained substantial aggregative abilities to form fibrils (70~80%) compared with wild-type A β 42 in Th-T test (Fig. 5F). (+)-Taxifolin did not suppress the aggregative ability of K16nL-A β 42 (Fig. 5B). K28nL-A β 42 also aggregated in the presence of (+)-taxifolin, though intensity of the Th-T fluorescence slightly decreased than that for K28nL-A β 42 alone (Fig. 5C). Moreover, (+)-taxifolin did not prevent the aggregation of K16,K28(nL)₂-A β 42 and R5,K16,K28(nL)₃-A β 42 (Figs. 5D and E). On the other hand, (+)-taxifolin largely suppressed the aggregation of R5nL-A β 42 (Fig. 5A). These results indicate that lysine residues at positions 16 and 28 could be targets for the oxidized taxifolin to prevent the aggregation of A β 42. More correctly, since the aggregative ability of K28nL-A β 42 was slightly suppressed by (+)-taxifolin compared with that of K16nL-A β 42 (Figs. 5B and C), Lys16 would be more specific target than Lys28 in inhibition of A β 42 aggregation.

Inhibition of A β 42 Aggregation by

Non-Catechol-Type Flavonoids—Myricetin, quercetin, morin, and kaempferol, which were previously reported to inhibit A β 42 aggregation, belong to the flavonols (43). Flavonols contain a double bond between C2 and C3 on the C-ring, whereas flavanonols like (+)-taxifolin do not (Fig. 6A). We calculated IC₅₀ for A β 42 aggregation from the inhibitory rate (%) of each flavonoid [10, 25, 50, 100 μ M for a strong-class inhibitor (dihydromyricetin, (+)-taxifolin, myricetin, quercetin); 25, 50, 100, 250 μ M for a middle-class inhibitor (morin, kaempferol, datiscetin); 50, 100, 250, 500 μ M for a weak-class inhibitor (dihydrokaempferol, pinobanksin, galangin)] on the aggregation of A β 42 (25 μ M) after a 24-h incubation. The values of IC₅₀ were summarized in Fig. 6A. Among flavanonols, dihydromyricetin (IC₅₀ = 25.3 μ M) as well as (+)-taxifolin (IC₅₀ = 33.0 μ M) with contiguous hydroxyl groups on the B-ring suppressed the aggregation of A β 42, whereas dihydrokaempferol and pinobanksin (IC₅₀ >500 μ M) with one or no hydroxyl group did not (Fig. 6A), suggesting vicinal hydroxyl groups on the B-ring to be essential for the inhibitory activity of flavanonols. Similarly, among flavonols, we compared the ability to inhibit A β 42 aggregation of myricetin, quercetin, morin, kaempferol, datiscetin, and galangin. The aggregation of A β 42 was strongly suppressed by myricetin (IC₅₀ = 15.1 μ M) and quercetin (IC₅₀ = 15.3 μ M) with vicinal hydroxyl groups on the B-ring, while galangin (IC₅₀ >500 μ M) without a hydroxyl group on the B-ring did not show any inhibitory activity (Fig. 6A). Interestingly, morin (IC₅₀ = 30.3 μ M), kaempferol (IC₅₀ = 75.1 μ M), and datiscetin (IC₅₀ = 55.4 μ M) without a catechol moiety moderately suppressed the aggregation of A β 42 (Fig. 6A). Regarding the relevance of auto-oxidation to the inhibition of A β 42 aggregation, we measured the Th-T fluorescence of A β 42 treated with these three non-catechol-type flavonols under an anaerobic condition or in the presence of TCEP. All these flavonols suppressed the aggregation of A β 42 even *in vacuo* (Fig. 6B). Moreover, addition of excess of TCEP (A β 42 : flavonols : TCEP = 25 : 50 : 200 μ M) did not affect the suppressive ability of these flavonols (data not shown), indicating

that the inhibition of non-catechol-type flavonols could not be ascribed to their auto-oxidation.

To gain further insight into the mechanism by which flavonoids inhibit A β 42 aggregation by targeting the Lys residues, aggregation tests were carried out in the presence of catechol-type flavonoids (dihydromyricetin, (+)-taxifolin, myricetin or quercetin), or non-catechol-type flavonols (morin, kaempferol, or datiscetin) using K16nL- and K16,K28(nL)₂-A β 42. We compared the aggregative ability of A β 42 mutant (25 μ M) incubated with each flavonoid (50 μ M), the concentration of which was the maximal value to suppress the fluorescence of A β 42 under 50% by (+)-taxifolin (data not shown). The catechol-type (+)-taxifolin and quercetin did not suppress the aggregation of these A β 42 mutants. Although dihydromyricetin and myricetin with contiguous trihydroxyl groups significantly prevented the aggregation of K16nL-A β 42, these flavonoids did not change the aggregative potency of K16,K28(nL)₂-A β 42 (Fig. 7A), implying that they could react with Lys28 as well as Lys16 because contiguous trihydroxyl groups might facilitate the auto-oxidation of the B-ring compared with (+)-taxifolin and quercetin containing vicinal hydroxyl groups. Notably, in the case of non-catechol-type flavonols (morin, kaempferol, and datiscetin), there was little difference in the inhibitory activity among the wild-type, K16nL-A β 42, and K16,K28(nL)₂-A β 42 (Fig. 7B). These results suggest the existence of another inhibitory mechanism for A β 42 aggregation by non-catechol-type flavonols other than the auto-oxidation followed by the Michael addition of Lys residues, as observed for (+)-taxifolin.

Analysis of the Interaction of A β 42 Aggregates with (+)-Taxifolin Using Solid-State NMR—Our recent study using a solid-state NMR showed that curcumin with an α,β -unsaturated ketone interacted with the aromatic hydrophobic core (A β 17-21) due to its inherent hydrophobicity and planarity, resulting in the inhibition of A β 42 aggregation *via* intercalation (18). Curcumin was reported to interact with A β 40 fibrils through the planarity of the enol form of curcumin (46).

Also given the preferable detection of monomeric A β 42 in LC-MS analysis, similar analysis was performed to clarify the interaction between A β 42 and (+)-taxifolin. (+)-Taxifolin was labeled with $^{13}\text{C}_6$ on the B-ring based on the previous structure-activity relationship studies, in which the catechol moiety on the B-ring is critical in the inhibitory potential, and the methylation of hydroxyl group at position 7 on the A-ring did not influence the aggregation of A β 42 (23). A β 42 was also ^{13}C -labeled site-specifically at Ala2, Ser8, Lys16, Val18, Phe19, and Phe20, in which only C $_{\alpha}$ was labeled in Phe19 and Phe20 to avoid the overlapping of the signals of A β 42 and (+)-taxifolin. For the broadband ^{13}C - ^{13}C correlation 2D experiments, dipolar-assisted rotational resonance (DARR) was employed (34). As shown in supplemental Fig. S2B, the interaction peaks between A β 42 and (+)-taxifolin were as weak as noise signals despite of the use of a ten-fold excess of (+)-taxifolin (A β 42 : (+)-taxifolin = 13 : 145 μM), while a five-fold excess was employed for curcumin (A β 42 : curcumin = 10 : 50 μM) (18). Remarkably, the ^{13}C - ^{13}C cross peaks between Lys-residues and B-ring of (+)-taxifolin was not observed significantly (Supplemental Fig. S2B). More specifically, the interaction of (+)-taxifolin with the aromatic hydrophobic core (A β 17-21), which was previously found in the curcumin case due to its inherent hydrophobicity and planarity (18) was not observed. These indicate that the inhibitory mechanism of A β 42 aggregation by (+)-taxifolin (*via* covalent bonding) could be different from that of curcumin (*via* intercalation).

Since lack of the double bond at positions 2 and 3 of (+)-taxifolin could decrease its planarity, it might not be able to insert into the β -sheet region of the A β 42 aggregate (Lys16~Ala21). Instability of the oxidized taxifolin-A β 42 adduct might be another reason. The previous solution-state NMR studies on myricetin and A β 42 (20) suggested the less-specific broad recognition of the β -sheet region, possibly due to the usage of excessive amounts of myricetin (A β 42 : myricetin = 25 : 200 μM). This finding might reflect the difference in suppressive ability between myricetin and (+)-taxifolin against

K16nL-A β 42 (Fig. 7A).

DISCUSSION

Thus far, the anti-AD activity of flavonoids has been believed to originate from their anti-oxidative activity and/or β -sheet recognition due to their hydrophobicity and planarity. However, these parameters are not necessarily accompanied by the ability to inhibit the aggregation of A β 42 and other amyloidogenic proteins (11). This background led us to reconsider whether the inhibitory activity can be simply explained by these “less-specific” properties (anti-oxidation, hydrophobicity, and planarity) or not.

On the basis of the present results, we propose a site-specific mechanism whereby catechol-type flavonoids inhibit the aggregation of A β 42, in which a catechol structure could be auto-oxidized to form the *o*-quinone on the B-ring, followed by the formation of the *o*-quinone-A β 42 adduct targeting Lys residues at positions 16 and 28 of A β 42, but not be originated from the anti-oxidative activity (Fig. 8). This could provide unique opportunities to design potent inhibitors of A β 42 aggregation. On the other hand, the inhibitory ability of non-catechol-type flavonols containing a double bond between C2 and C3 on the C-ring (Fig. 6A) does not require the auto-oxidation. The data in Figs. 6 and 7 indicate that the interaction of non-catechol-type flavonols with A β 42 might be less effective than the conjugate addition of the Lys residues to the *o*-quinone moiety derived from auto-oxidation. These findings might explain in part the difference in the inhibitory ability between flavanols and flavonols.

Our previous investigation using solid-state NMR together with systematic proline replacement identified a toxic conformer with a turn at positions 22 and 23 in A β 42 (47), and proposed that the residues at positions 15-21 and 24-32 containing Lys 16 and Lys 28 are involved in the intermolecular β -sheet region, whereas the N-terminal 13 residues are not (48). A monoclonal antibody against the toxic turn at positions 22 and 23 detected A β oligomers in

human AD brain (49) and induced pluripotent stem cells (50) as well as in AD mice (51,52). As mentioned above, an attempt to determine the Lys residues involved in the adduct formation by LC-MS-MS analysis gave disappointing results, possibly because of the extremely low amount and/or instability of the adducts. Since the targeted Lys-residues (Lys16 and 28), not the Arg residue (Arg5), are incorporated in the intermolecular β -sheet region (Fig. 8), even a small amount of covalently-bonded adducts at the Lys residues of A β 42 oligomers and/or protofibrils could inhibit the formation of A β 42 aggregates (fibrils) detected by the Th-T fluorescence.

Recently, Bitan's group reported that the Lys-specific synthetic compound (molecular tweezer, CLR01) prevented the cytotoxicity and oligomerization of A β 42 through non-covalent interaction *in vitro* (53) and *in vivo* (54). Their subsequent study using A β 42 mutants substituted at Lys16 or Lys28 with Ala revealed a key role for Lys residues in A β 42-induced neurotoxicity rather than aggregation (55). These reports did not contradict the results that the aggregates of double and triple mutants [K16,K28(*nL*)₂-A β 42 and R5,K16,K28(*nL*)₃-A β 42] after 24-h of incubation were slightly less than that of wild-type A β 42 in this study (Fig. 5F).

R5*nL*-A β 42 (~4 h) and K28*nL*-A β 42 (~2 h) had the nucleation phase (Fig. 5A, C), while three A β 42 mutants [K16*nL*-A β 42, K16,K28(*nL*)₂-A β 42, and R5,K16,K28(*nL*)₃-A β 42] including the substitution of K16 with *nL* did not (Fig. 5B, D, E). These mean that the aggregative ability of K16*nL*-A β 42 seems to be more potent than that of K28*nL*-A β 42. Because Lys16 residue is located at a hydrophobic cavity in the β -sheet region (56), the substitution with norleucine without an amino group could enhance the hydrophobic interaction in A β 42 aggregates, leading to passing the nucleation phase. In contrast, Lys28 was involved in the formation of salt bridge between Asp23 and Lys28 for A β 42 aggregation (56). These findings imply the different role of lysine residues at positions 16 and 28 in A β 42 aggregation, which might explain the

difference of aggregative ability between K16*nL*- and K28*nL*-A β 42.

Notably, the nucleation phase of R5*nL*-A β 42 (~4 h) was partially longer than that of wild-type A β 42 (~1 h) (Fig. 1B, F and 5A). Since the flexibility of N-terminal region has been thought to be essential for aggregation of A β 42 (56), the replacement of Arg5 with norleucine might retard the nucleation phase in wild-type A β 42 aggregation by increasing hydrophobic interaction. Moreover, given no nucleation phase of three A β 42 mutants of Lys16, it is not surprising that (+)-taxifolin did not largely alter the aggregation properties of these mutants, because (+)-taxifolin could specifically target the elongation phase in wild-type A β 42 aggregation, rather than the nucleation phase.

LeVine *et al.* suggested preventive effects on A β 42 aggregation by several dihydroxybenzoic acid isomers, in which 2,3- and 3,4-dihydroxy benzoic acids delayed the velocity of oligomer formation (57). Fisetin, a quercetin analogue without the 5-OH group on the A-ring, also inhibited the aggregation of A β 42 (58). Ushikubo *et al.* reported that 7-OH group on the A-ring is not involved in the anti-aggregative ability of flavonols (59). These are consistent with our previous study on the structure-activity relationship of (+)-taxifolin (23). On the other hand, lacmoid without a catechol moiety bound less-specifically to A β 42 (60). These findings together with the present results strongly support that flavonoids with vicinal hydroxyl groups on the B-ring could be indispensable to bind covalently with A β 42 to suppress its aggregation. It is also reasonable that 3,4,5-trihydroxybenzoic acid, gallic acid (57) and 3',4',5'-trihydroxyflavone (59) as well as dihydromyricetin (Figs. 6A) suppressed the aggregation of wild-type A β 42. In particular, the inhibitory activities of dihydromyricetin, (+)-taxifolin, myricetin, and quercetin were higher than those of morin, kampferol, and datiscetin (Fig. 6A), suggesting that the nucleophilic addition to the *o*-quinone moiety by the Lys residues of A β 42 could contribute more significantly to the inhibition of A β 42 aggregation than the hydrophobic interaction.

However, additional role of the A- and C-rings of catechol-type flavonoids in the suppression of A β 42 aggregation is not negligible, since the inhibitory activity of catechol itself was low (61).

Fink and colleagues previously proposed the contribution of interaction of Lys residues with the baicalein *o*-quinone to the inhibition of α -synuclein responsible for Parkinson's disease (45). However, the underlying molecular mechanism cannot be fully explained by the oxidized baicalein because the aggregation of α -synuclein was inhibited by baicalein even under an anaerobic condition (45). Quite recently, the oxidation product of EGCG was in part involved in remodeling the preformed fibrils of A β 40 by EGCG (62).

To the best of our knowledge, this is a first report that dihydromyricetin and datiscetin as well as (+)-taxifolin have anti-aggregative activity against A β 42. We also demonstrated that (+)-taxifolin could suppress the elongation phase

in the aggregation of wild-type A β 42, rather than the nucleation phase. Seed extracts of *Silybum marianum*, known as silymarin, have long been used as an anti-hepatotoxic medicine without notable adverse effects (63), and in particular, are efficacious against damage induced by alcohol and disturbances in the function of the gastrointestinal tract (64). Booth *et al.* showed that (+)-taxifolin was not toxic when given long term to albino rats (65). Therefore, (+)-taxifolin may be a worthy candidate for AD therapeutics. Although some polyphenols [naringenin (66) and curcumin (67)] were reported to pass through the blood-brain barrier after oral administration, caution should be used because of the difference between animal and clinical condition.

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FOOTNOTES

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[†]Research Fellow of the Japan Society for the Promotion of Science.

¹The abbreviations used are: A β , amyloid β -protein; AD, Alzheimer's disease; ANOVA, analysis of variance; CD, circular dichroism; EGCG, (-)-epigallocatechin-3-gallate; EI-MS, electron ionization-mass spectrometry; HPLC, high performance liquid chromatography; LC-MS, liquid chromatography-mass spectrometry; MALDI-TOF-MS, matrix-assisted laser desorption/ionization time-of-flight mass spectrometry; NMR, nuclear magnetic resonance; PBS, phosphate-buffered saline; TCEP, tris(2-carboxyethyl)phosphate; TEM, transmission electron microscopy; Th-T, thioflavin-T; UV, ultraviolet.

FIGURE LEGENDS

Fig. 1. Effects of auto-oxidation of (+)-taxifolin on its ability to inhibit A β 42 aggregation and Met35 oxidation. *A*, The structure of (+)-taxifolin. *B*, The effect of sodium periodate (NaIO₄), an oxidant, on A β 42 aggregation estimated by Th-T tests. A β 42 (25 μ M) was incubated with or without (+)-taxifolin (50 μ M) and/or NaIO₄ (100 μ M) at 37 °C. *C*, The ability of (+)-taxifolin to suppress the aggregation of A β 42 under an anaerobic condition. A β 42 (25 μ M) was incubated with or without (+)-taxifolin (50 μ M) *in vacuo* at room temperature. *D*, HPLC analysis of A β 42 solution with the indicated treatment. A β 42 (25 μ M) was incubated with or without (+)-taxifolin (50 μ M) and/or NaIO₄ (100 μ M) at 37 °C for 4 h. An aliquot was centrifuged by 20,130 g at 4 °C for 10 min, and the supernatant was subjected to HPLC on a Develosil ODS UG-5 column under a gradient of 10-50% CH₃CN containing 0.1% NH₄OH for 40 min. *E*, The effect of tris(2-carboxylethyl)phosphine hydrochloride (TCEP-HCl denoted as TCEP), a reductant, on A β 42 aggregation. A β 42 (25 μ M) was incubated with or without (+)-taxifolin (50 μ M) and/or TCEP (100 μ M) at 37 °C. *F*, The aggregative ability of A β 42 in the presence of A β 42 seed and/or (+)-taxifolin, NaIO₄. A β 42 (25 μ M) was incubated with or without the seed (10 μ g/mL) and/or (+)-taxifolin (50 μ M), NaIO₄ (100 μ M) at 37 °C. The data are presented as the mean \pm s.e.m. ($n = 8$). Th-T relative fluorescence was expressed as a percentage of the fluorescence for wild-type A β 42 alone, whose maximum value was taken as 100%.

Fig. 2. Effects of auto-oxidation of (+)-taxifolin on the morphology of A β 42 aggregates. *A*, TEM images of A β 42 aggregates after 48 h of incubation. A β 42 (25 μ M) was treated with or without (+)-taxifolin (50 μ M) and/or NaIO₄ (100 μ M) under an aerobic or anaerobic condition. Scale bar = 200 nm. *B*, UV-visible spectra of (+)-taxifolin (50 μ M) treated with A β 42 (25 μ M) in the presence of NaIO₄ (100 μ M) or TCEP (100 μ M) after incubation for 0, 4, 8, 24, and 48 h, respectively.

Fig. 3. Effects of auto-oxidation of (+)-taxifolin on its ability to prevent the transformation into the β -sheet structure of A β 42 using CD spectrometry. *A-C*, A β 42 (25 μ M) was incubated (*A*) without, with (+)-taxifolin (50 μ M) in the (*B*) absence or (*C*) presence of NaIO₄ (100 μ M) at 37 °C for the period indicated. *D, E*, A β 42 (25 μ M) was incubated (*D*) without or (*E*) with (+)-taxifolin (50 μ M) *in vacuo* at room temperature for the period indicated.

Fig. 4. LC-MS analysis of A β 42 treated with oxidized taxifolin. *A*, The proposed structures of the adducts between oxidized taxifolin and A β 42. (*Upper*) Lys16, Lys28, and (*lower*) Arg5 in A β 42 could attack the *o*-quinone of (+)-taxifolin, resulting in (*left*) Michael addition or (*right*) Schiff base formation with the indicated calculated mass. *B*, LCMS-IT-TOF analysis of the A β 42 solution treated with oxidized taxifolin. After A β 42 (25 μ M) was incubated with (+)-taxifolin (50 μ M) in the presence of NaIO₄ (100 μ M) at 37 °C for 4 h, an aliquot was subjected to the analysis.

Fig. 5. Effects of (+)-taxifolin on the aggregation of A β 42 mutants substituted with norleucine (*nL*). The aggregative ability of *A*, R5*nL*-A β 42, *B*, K16*nL*-A β 42, *C*, K28*nL*-A β 42, *D*, K16,K28(*nL*)₂-A β 42, and *E*, R5,K16,K28(*nL*)₃-A β 42 in the presence of (+)-taxifolin was examined by Th-T assay. Each A β 42 mutant (25 μ M) was incubated with or without (+)-taxifolin (50 μ M) at 37 °C. The data are presented as the mean \pm s.e.m. ($n = 8$). Th-T relative fluorescence was expressed as a percentage of the fluorescence for A β 42 mutant alone, whose maximum value was taken as 100%. * $p < 0.05$ compared with A β 42 mutant alone. The time point without asterisk means no significant difference between A β 42 mutant treated and untreated with (+)-taxifolin. *F*, The comparison of

aggregative ability of A β 42 mutants. Th-T relative fluorescence of each mutant after incubation for 24 h was expressed as a percentage of the fluorescence for wild-type A β 42 alone, whose maximum value was taken as 100%. The data are presented as the mean \pm s.e.m. ($n = 8$).

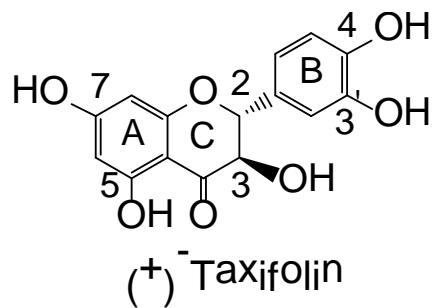
Fig. 6. Effects of flavanonols and flavonols on the aggregation of A β 42. *A*, The structures and IC₅₀ values of (*upper*) flavanonols and (*lower*) flavonols examined in this study. The IC₅₀ value was calculated from the inhibitory rate (%) of each flavonoid on A β 42 aggregation after 24 h incubation using Th-T assay. *B*, A β 42 (25 μ M) incubated with morin, kaempferol, or datiscetin (50 μ M) *in vacuo* at room temperature. Th-T relative fluorescence was expressed as a percentage of the fluorescence for A β 42 alone, whose maximum value was taken as 100%.

Fig. 7. Effects of flavanonols and flavonols on the aggregation of A β 42 mutants. *A*, The aggregative ability of A β 42 mutants (25 μ M) incubated with a catechol-type flavanonol or flavonol (50 μ M) for 24 h estimated by Th-T tests. The data are presented as the mean \pm s.e.m. ($n = 8$). Th-T relative fluorescence was expressed as a percentage of the fluorescence for each A β 42 alone, whose value at 24 h was taken as 100%. *B*, The aggregative ability of A β 42 mutants (25 μ M) treated with a non-catechol-type flavonol (50 μ M) for 24 h, estimated by Th-T tests. * $p < 0.05$. n.s. = not significant.

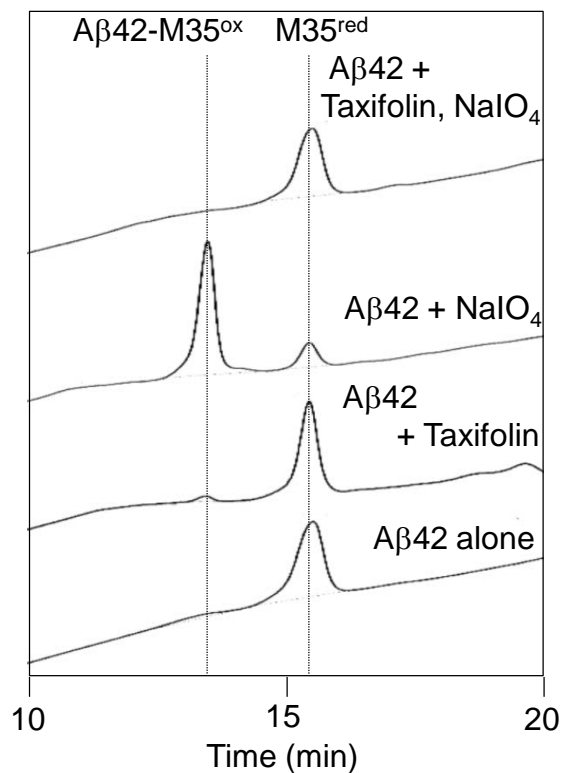
Fig. 8. Site-specific inhibitory mechanisms of A β 42 aggregation by catechol-type flavonoids. Catechol-type flavanonols (*e.g.* (+)-taxifolin) or flavonols (*e.g.* quercetin) were oxidized to form corresponding *o*-quinones on B-ring, followed by the formation of adducts by Lys16 and Lys28 of A β 42. Because Lys16 and Lys28 are incorporated in the intermolecular β -sheet region (8), A β 42 aggregates would be destabilized by the adduct formation.

Figure 1

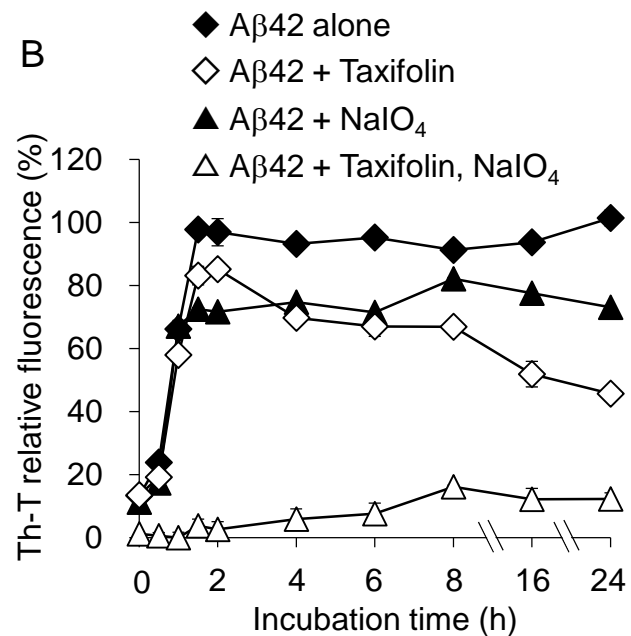
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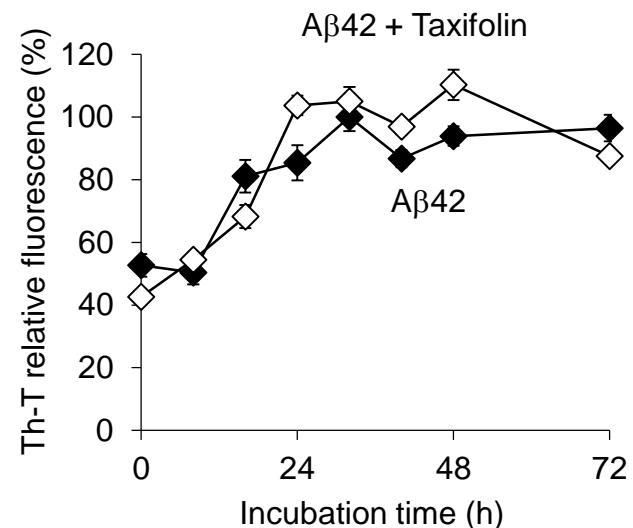
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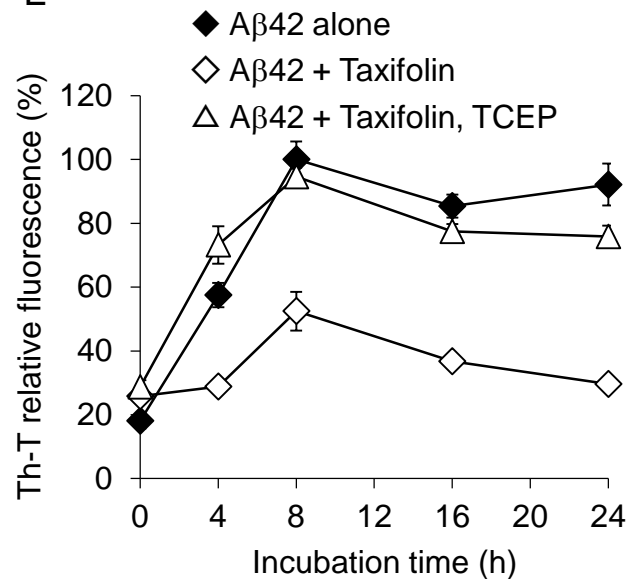
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C



E



F

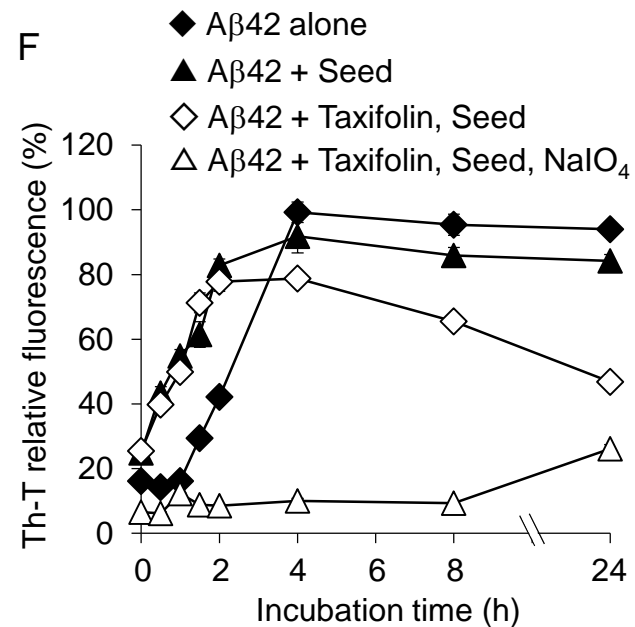
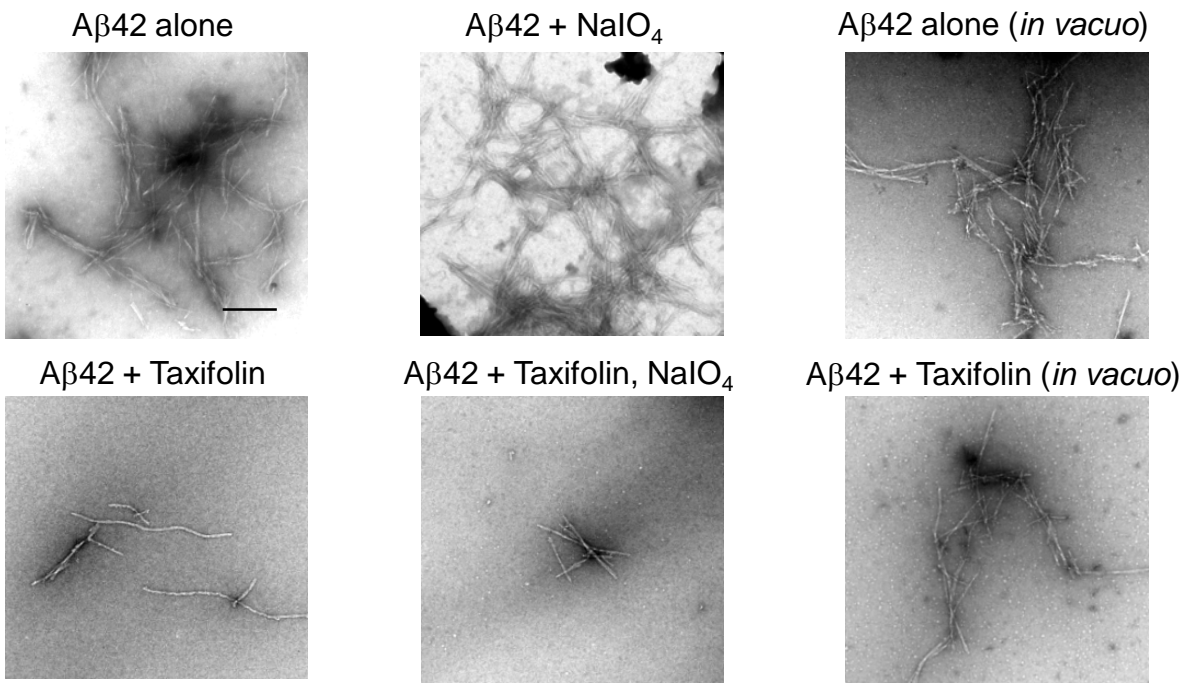


Figure 2

A



B

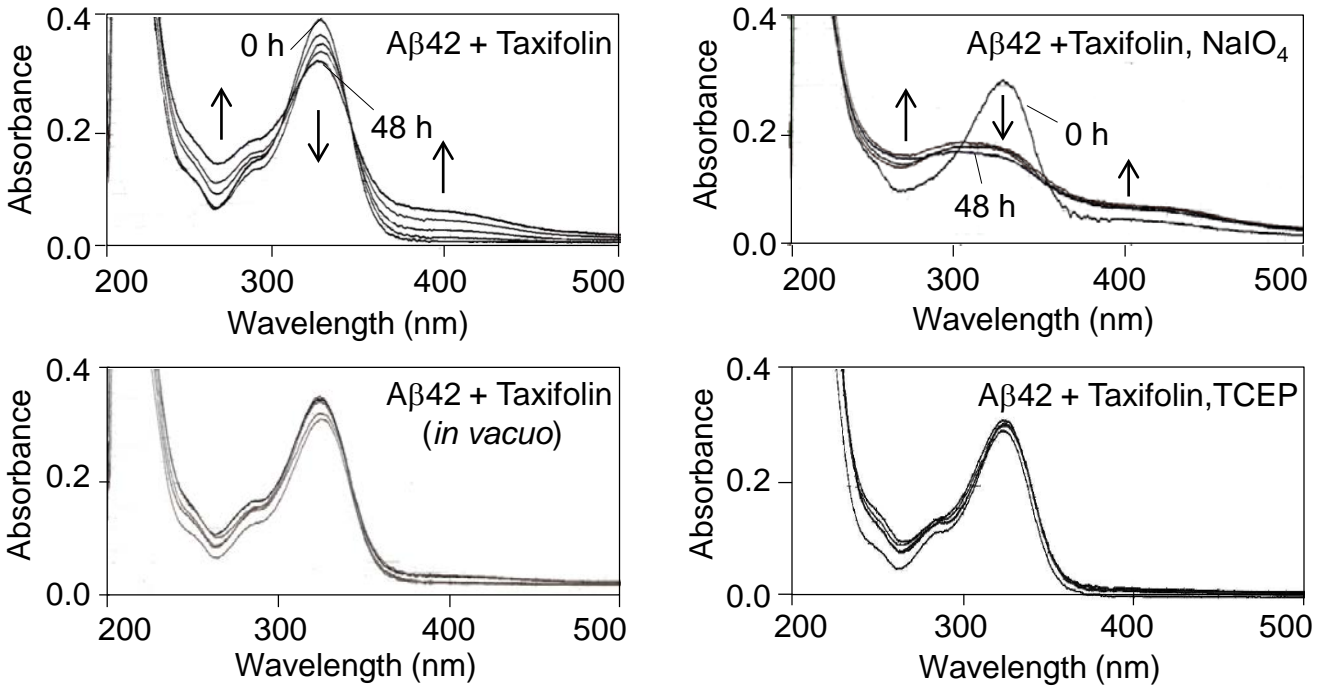


Figure 3

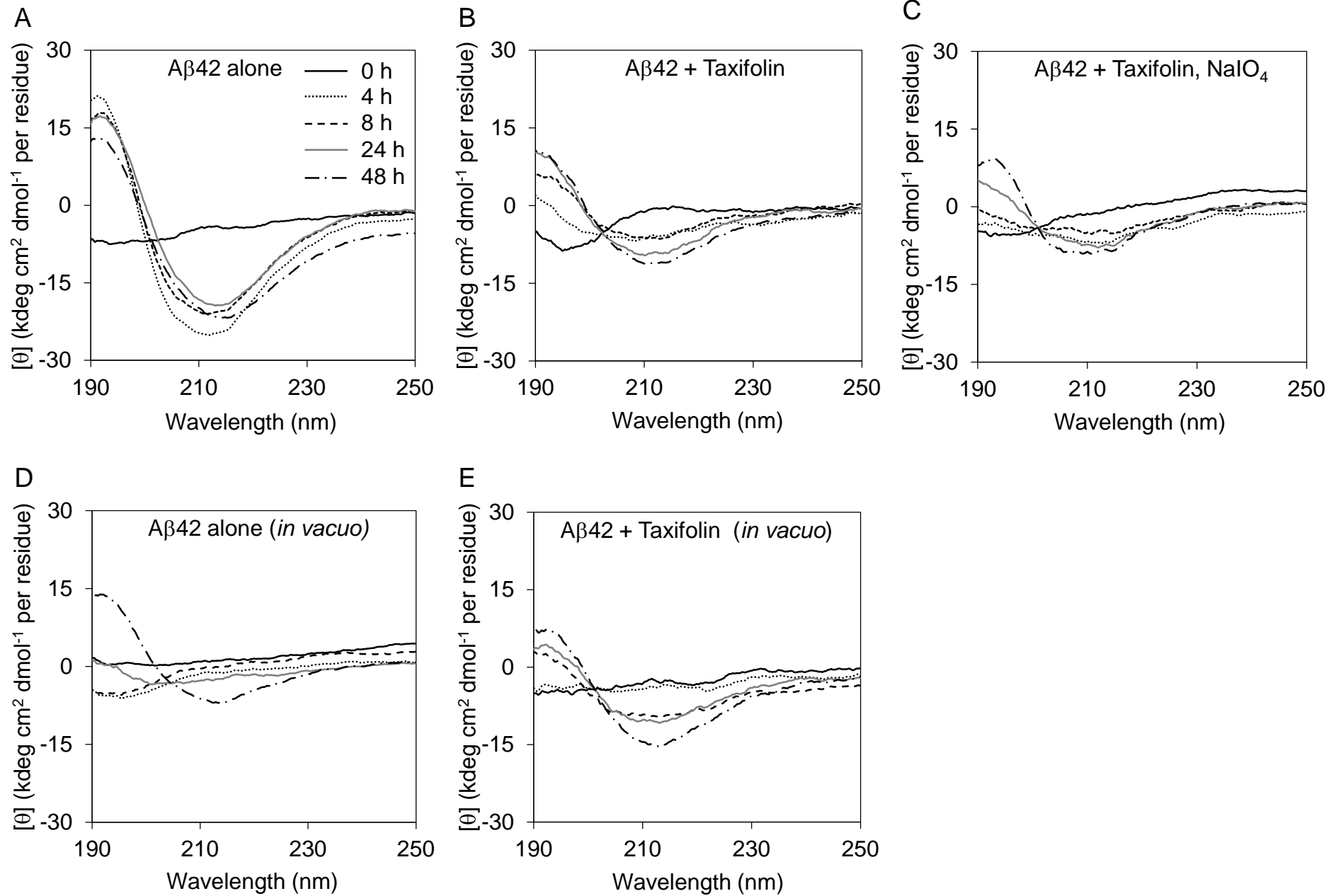
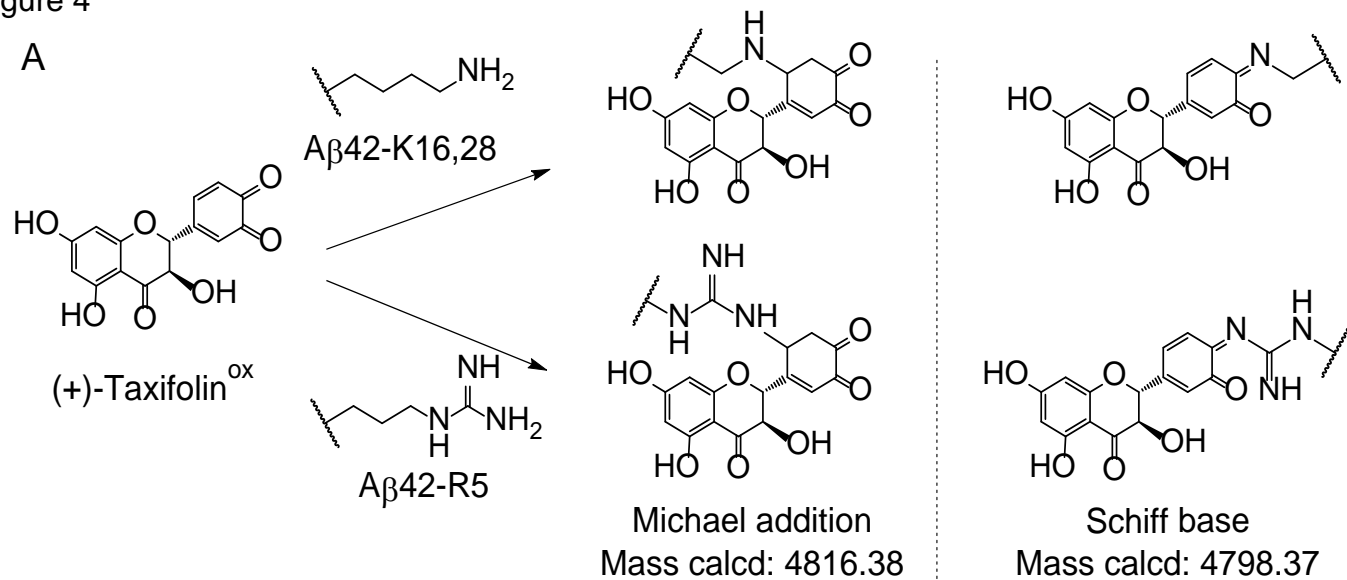


Figure 4

A



B

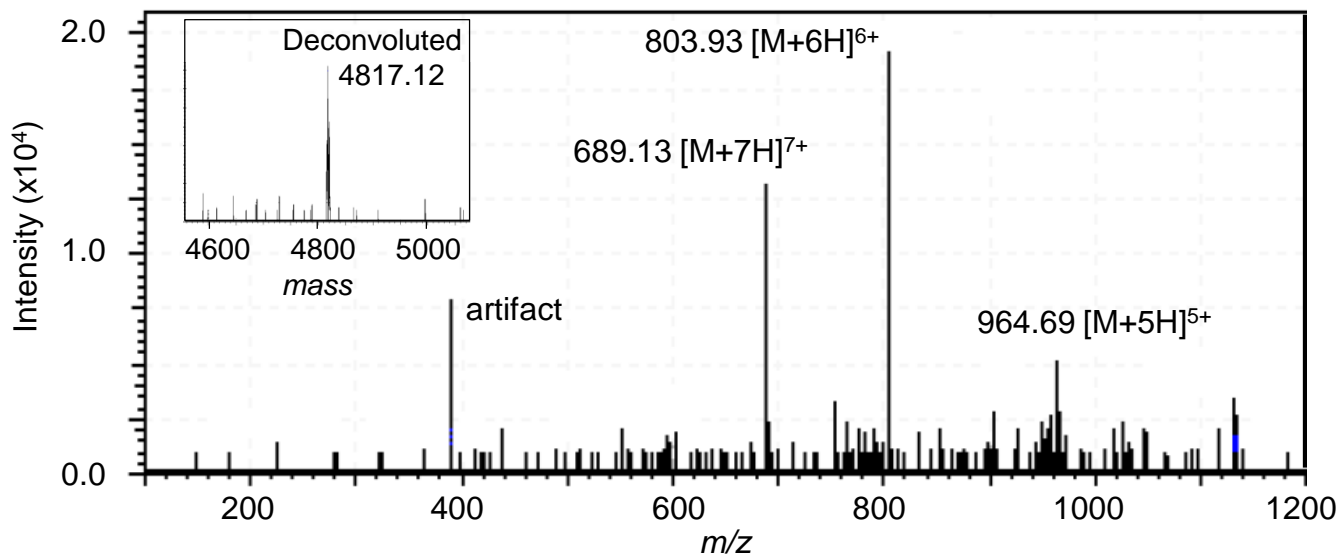


Figure 5

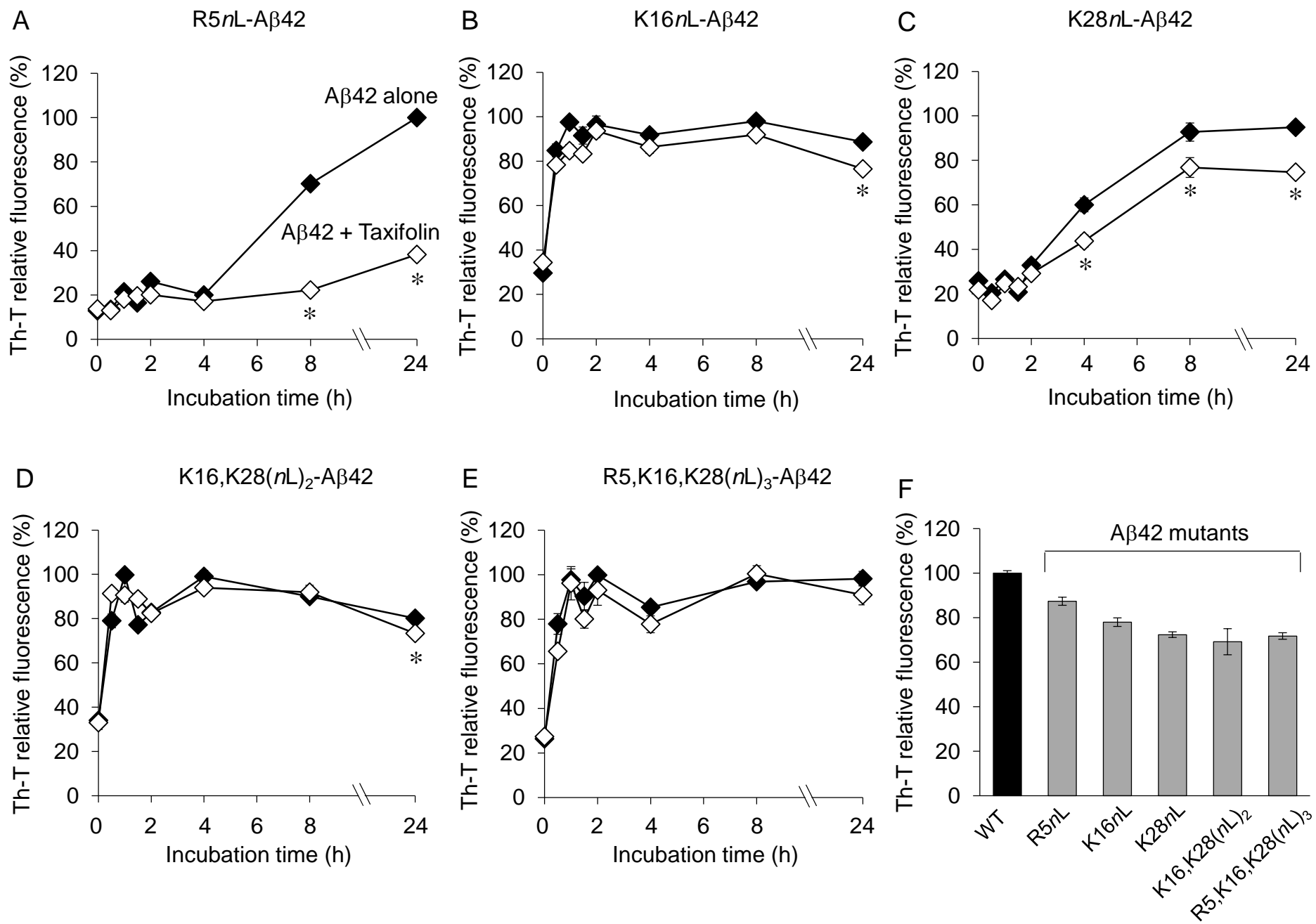
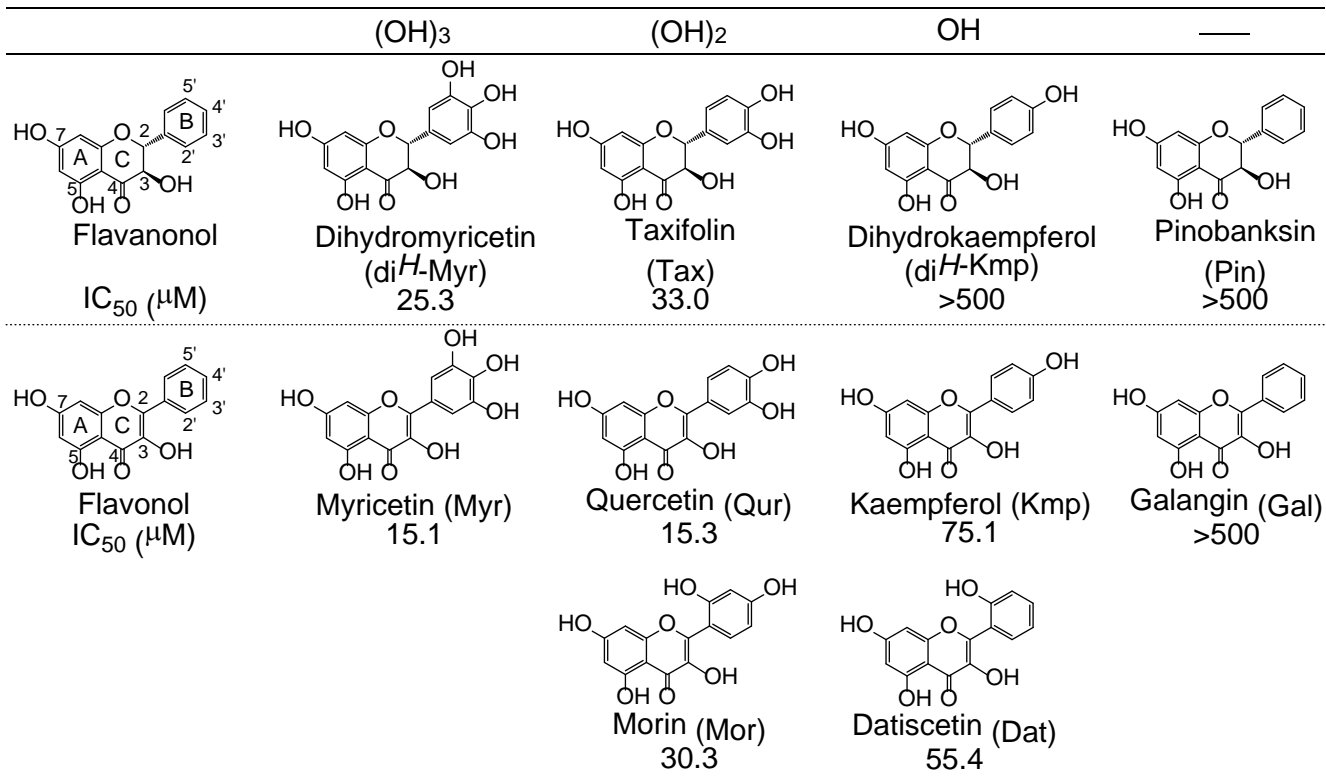


Figure 6

A



B

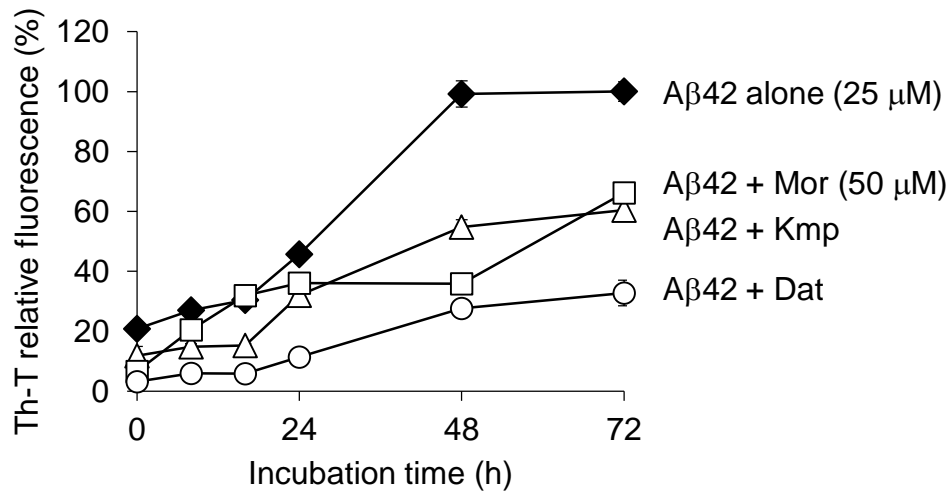


Figure 7

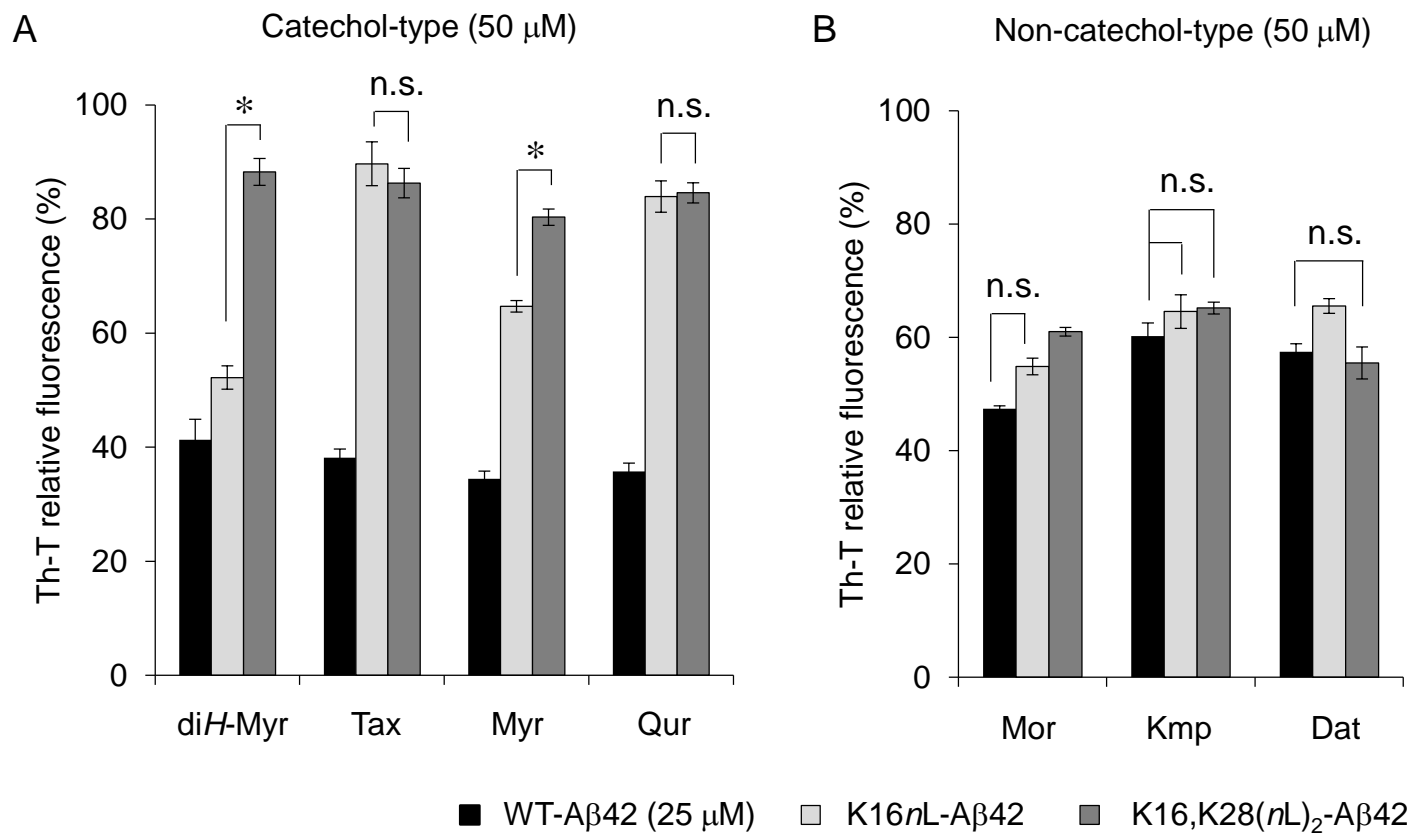
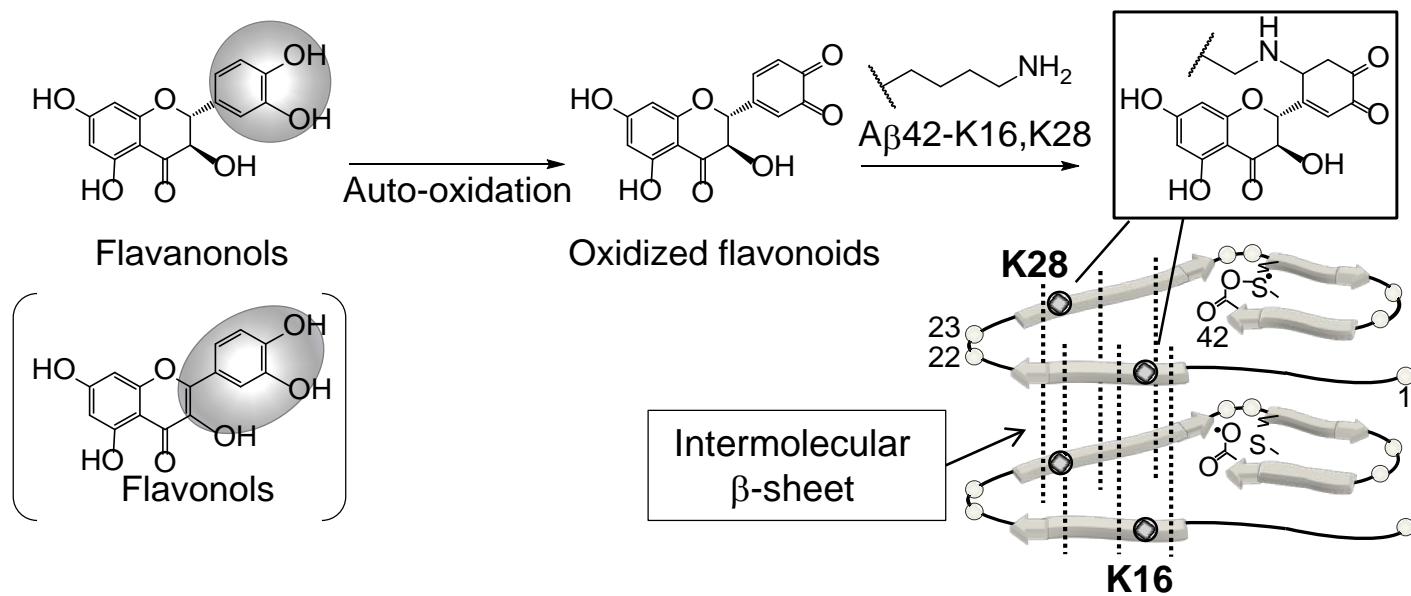


Figure 8



Supplemental Data

Site-specific Inhibitory Mechanism for A β 42 Aggregation by Catechol-Type Flavonoids Targeting the Lys-Residues*

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*Running title: *Inhibitory Mechanisms of A β 42 aggregation by Flavonoids*

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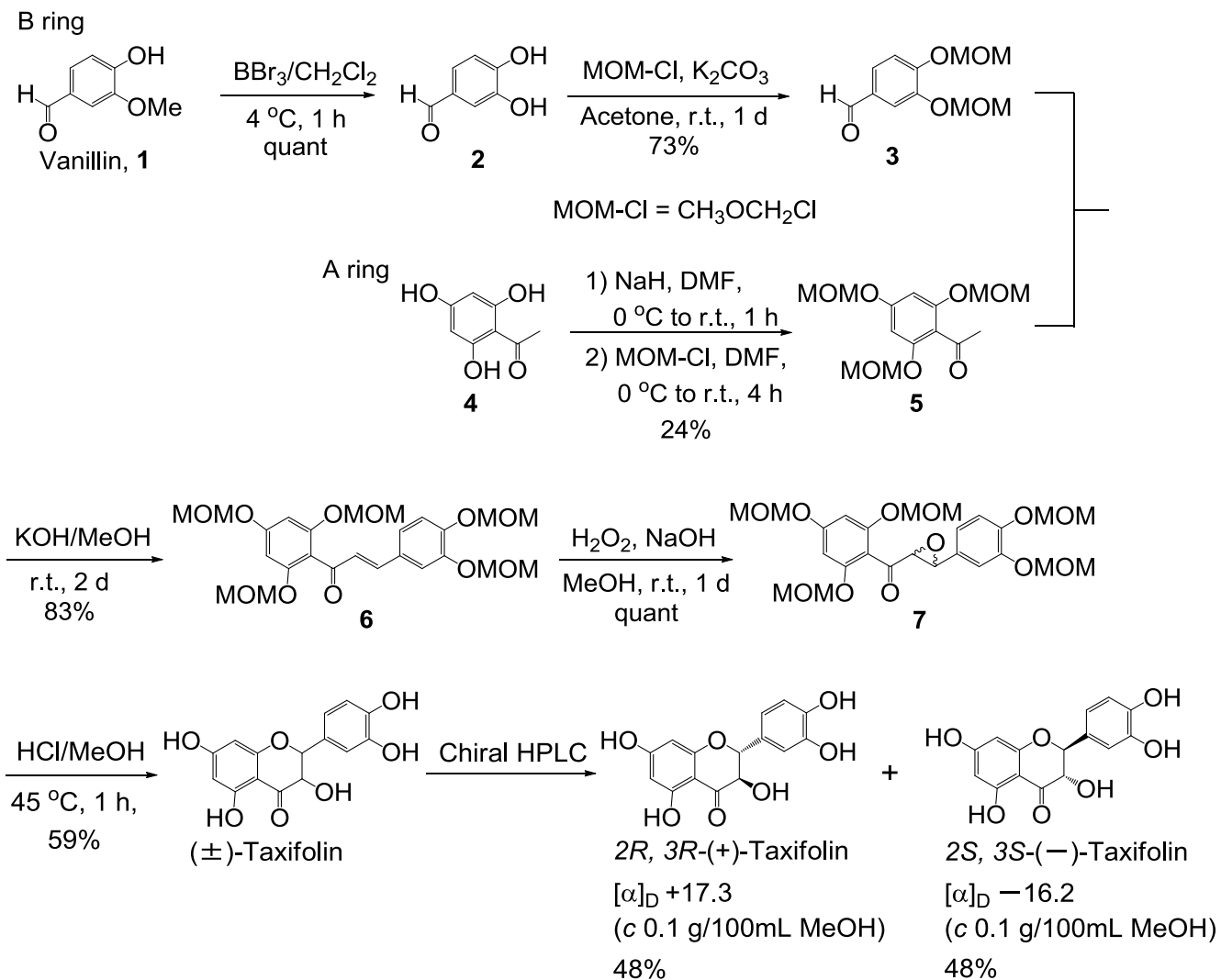
Supplemental Scheme S1. Synthesis of (+)-taxifolin and trapping of taxifolin *o*-quinone. **A**, Route of (+)-taxifolin synthesis. Dihydrokaempferol and pinobanksin were synthesized in a similar manner to (+)-taxifolin using 4-hydroxybenzaldehyde or benzaldehyde in place of vanillin as a starting material. **B**, Trapping of (\pm)-taxifolin *o*-quinone by using *o*-phenyldiamine to form the corresponding phenazine.

Supplemental Fig. S1. NMR spectra of ¹³C₆(+)-taxifolin. **A**, ¹H NMR spectrum of ¹³C₆(+)-taxifolin. ¹H NMR (500 MHz, 295.2 K, acetone-*d*₆, 7.7 mM) δ 4.61 (1H, dd, *J* = 11.5, 3.0 Hz), 5.01 (1H, dq, *J* = 11.5, 4.0 Hz), 5.95 (1H, d, *J* = 2.4 Hz), 5.99 (1H, d, *J* = 2.4 Hz), 6.98 (2H, dm, *J* = 157.0 Hz), 7.07 (1H, dm, *J* = 157.0 Hz), 11.7 (1H, s). **B**, ¹³C NMR spectrum of ¹³C₆(+)-taxifolin. ¹³C NMR (500 MHz, 295.2 K, acetone-*d*₆, 7.7 mM) δ 73.2, 84.7, 96.1, 101.5, 115.9, 120.8, 129.9, 146.8, 164.2, 165.1, 168.2, 198.0.

Supplemental Fig. S2. Solid-state NMR spectra of A β 42 aggregates associated with (+)-taxifolin. **A**, 1D ¹³C CP/MAS spectra. A β 42 labeled at Ala2, Ser8, Lys16, Val18, Phe19, and Phe20, in which only C β was labeled in Phe19 and Phe20, and ¹³C₆(+)-taxifolin on the B-ring were used. Molar ratio, A β 42 : (+)-taxifolin = 1 : 11. **B**, 2D Covariance-processed DARR spectra at a mixing time of (*left*) 50 ms and (*right*) 500 ms. In the spectrum at 50 ms, the distance between carbon atoms with cross peaks is 1.5-3.0 Å, whereas at 500 ms it is 1.5-5.0 Å. In the spectrum at 500 ms, intermolecular cross peaks were as weak as noise signals in the region framed by the line. **C**, 2D FT-DARR spectra at mixing time of (*left*) 50 ms and (*right*) 500 ms. The number of acquisition was 400 scans per increment.

Scheme S1

A



B

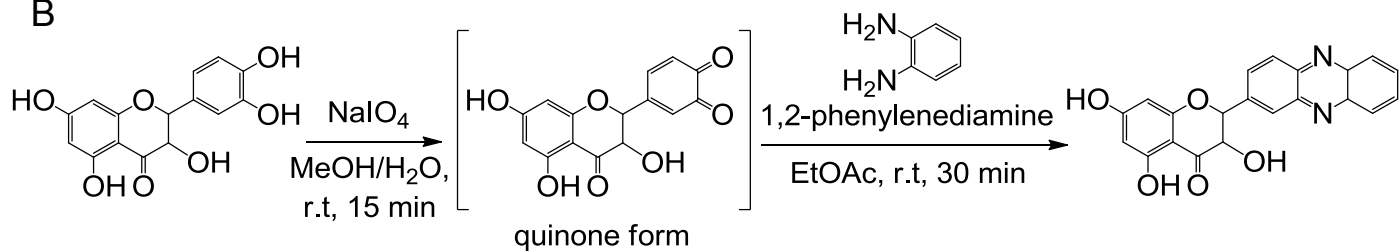
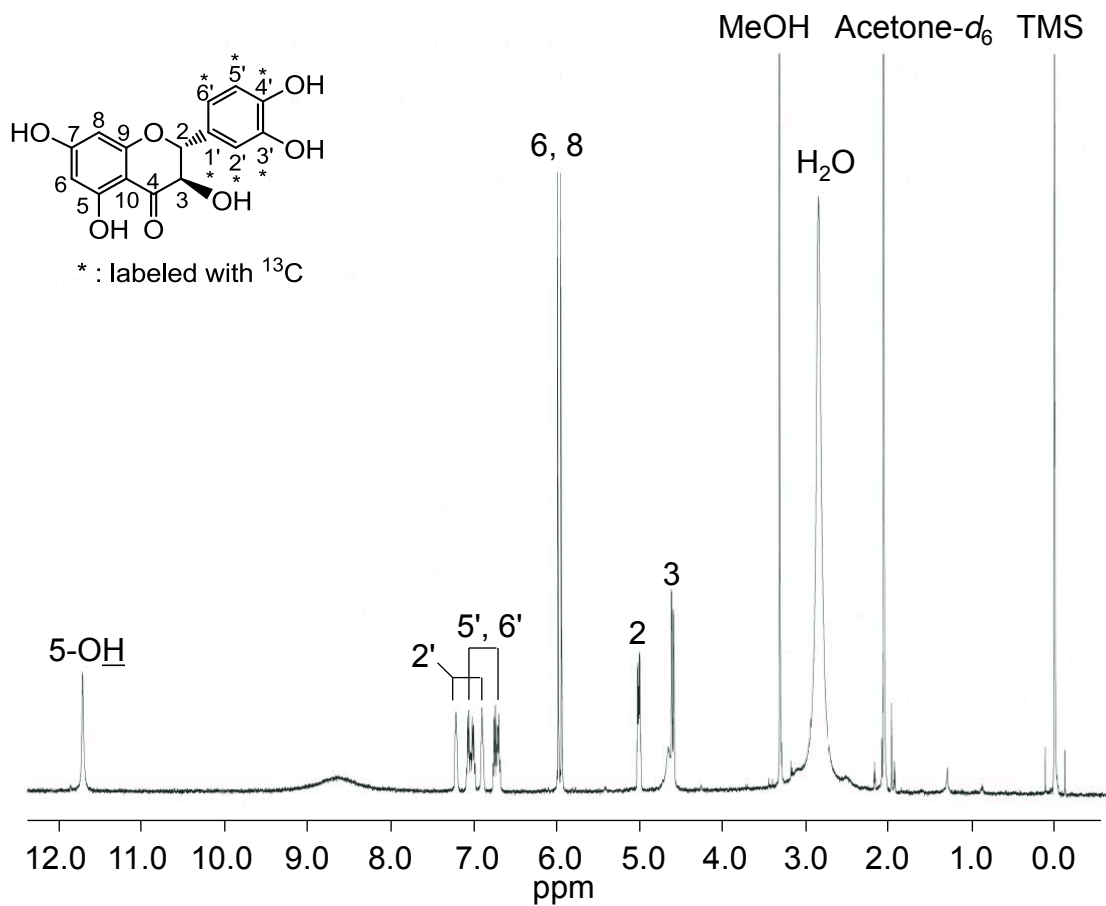


Figure S1

A



B

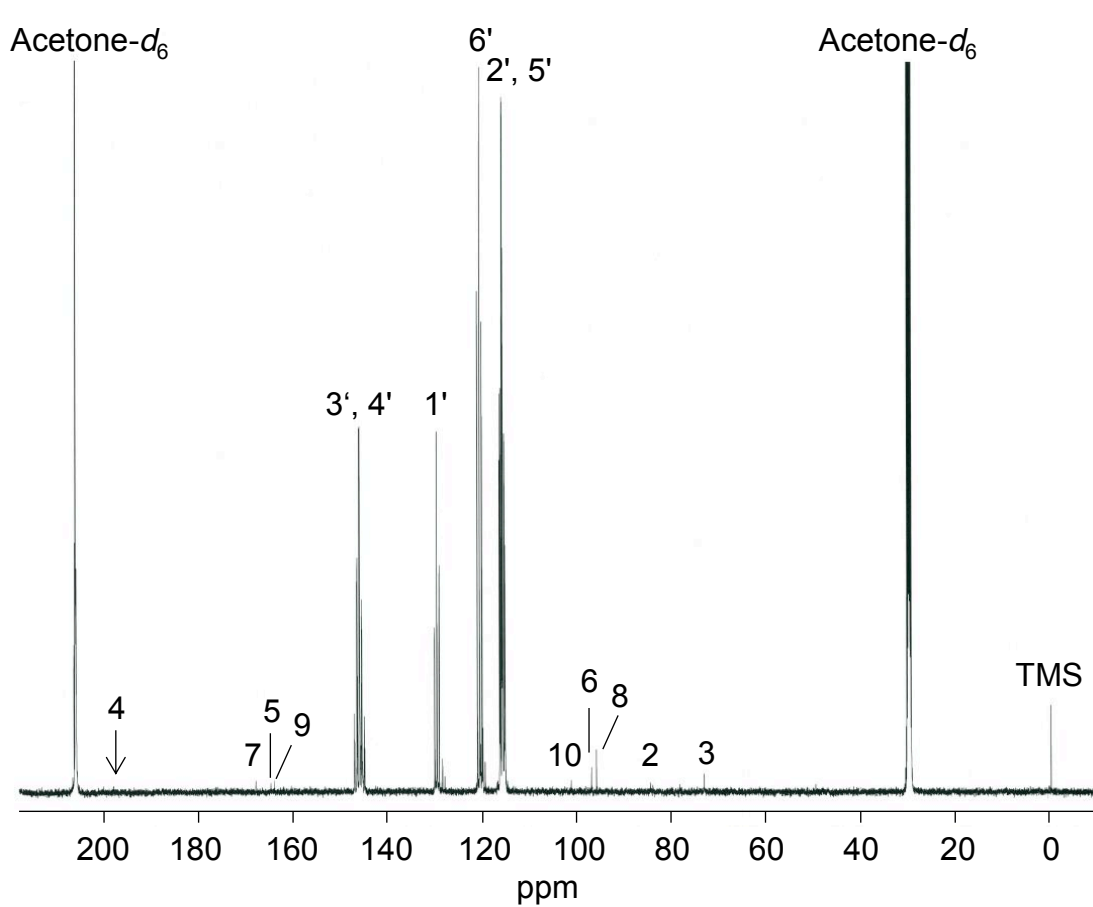


Figure S2

