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The effect of α -tocopherol, α - and γ -tocotrienols on amyloid- β aggregation and disaggregation in vitro

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ABSTRACT

One of the neuropathological hallmarks of Alzheimer's disease (AD)—causing neurodegeneration and consequent memory deterioration, and eventually, cognitive decline—is amyloid- β (A β) aggregation forming amyloid plaques. Our previous study showed the potential of a tocotrienol-rich fraction—a mixture of naturally occurring of vitamin E analogs—to inhibit A β aggregation and restore cognitive function in an AD mouse model. The current study examined the effect of three vitamin E analogs— α -tocopherol (α -TOC), α -tocotrienol (α -T3), and γ -tocotrienol (γ -T3)—on A β aggregation, disaggregation, and oligomerization in vitro. Thioflavin T (ThT) assay showed α -T3 reduced A β aggregation at 10 μ M concentration. Furthermore, both α -T3 and γ -T3 demonstrated A β disaggregation, as shown by the reduction of ThT fluorescence. However, α -TOC showed no significant effect. We confirmed the results for ThT assays with scanning electron microscopy imaging. Further investigation in photo-induced cross-linking of unmodified protein assay indicated a reduction in A β oligomerization by γ -T3. The present study thus revealed the individual effect of each tocotrienol analog in reducing A β aggregation and oligomerization as well as disaggregating preformed fibrils.

1. Introduction

Alzheimer's disease (AD), the most common cause of dementia in the elderly, is a progressive neurodegenerative disorder that affects the memory and cognitive function of an individual. The two neuropathological hallmarks of AD are the accumulation of amyloid- β (A β) peptides to form senile plaques, and hyperphosphorylation of tau protein to form neurofibrillary tangles. Both events lead to synaptic and neuronal dysfunction and—eventually—to impaired cognitive performance [1]. The imbalance between production of A β in the brain and its clearance causes accumulation and eventually, AD pathogenesis, to occur [2]. A β fibrillization begins with the polymerization of soluble A β oligomers to form A β fibrils and plaques [3]. The accumulation of A β oligomers to form A β fibrils is driven by the interaction between aromatic residues of A β peptides [4]. Studies have shown that small aromatic molecules such as polyphenols can inhibit this interaction [5].

In a previous study, our group [6] revealed that tocotrienol-rich fraction (TRF) inhibited the formation of A β fibrils and A β oligomers in vitro. TRF is a natural mixture of vitamin E analogs derived from the palm oil of the *Elaeis guineensis* tree. It comprises two vitamin E series: tocotrienol (α -, β -, γ -, and δ -T3) and α -tocopherol (α -TOC). The series are distinguished by the presence of three double bonds at the side chain of the tocotrienol structure (Fig. 1). Vitamin E has shown beneficial effects in reducing the progression of degenerative diseases such as AD [7]. Many studies have identified vitamin E as an excellent antioxidant, anti-aging, and anti-inflammatory compound [8].

Our earlier findings provide insights into the effects of TRF on AD—particularly, via modulating amyloid pathology. However, the identity of the vitamin E analog in TRF exerting a better neuroprotective effect in terms of reducing amyloid pathology in vitro and in vivo—and hence, contributing to an improved cognitive function—remains unknown. A study by Khanna et al. [9] revealed that α -T3 at a nanomolar

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concentration provides more potent neuroprotection than that provided by α -TOC. However, no studies have investigated its effect on A β aggregation and disaggregation in vitro. Our current study therefore examined the effect of individual vitamin E analogs—particularly α -TOC, α -T3, and γ -T3—on A β aggregation and disaggregation in vitro.

2. Materials and methods

2.1. Preparation of α -TOC, α -T3, and γ -T3

We purchased α -TOC and α -T3 from Sigma-Aldrich (St. Louis, MO, USA), and γ -T3 from Cayman Chemical (Ann Arbor, Michigan, USA). We prepared a stock solution of 10 mM by dissolving it in ethanol and kept it at -30 °C until use. We carried out further dilutions using phosphate-buffered saline (PBS; Nacalai Tesque, Kyoto, Japan).

2.2. Preparation of A β 42 aggregates

We prepared human A β 1-42 peptide (A β 42; Peptide Institute, Osaka, Japan) as described elsewhere [6]. To examine the effects of α -TOC, α -T3, and γ -T3 on A β 42 aggregation, we mixed A β 42, individually, with α -TOC, α -T3, and γ -T3 to a final concentration of 10 μ M A β 42 plus 10, 30, 100, or 300 μ M α -TOC, α -T3, or γ -T3. We used PBS containing ethanol at 0.3% or 3% as a control. We incubated the mixtures at 37 °C for 5, 10, and 24 h.

We further investigated the disaggregation effect of α -TOC, α -T3, and γ -T3 on A β 42 fibrils preformed by the incubation at 37 °C for 3 h. We individually added α -TOC, α -T3, and γ -T3 to the A β 42 fibrils to reach a final concentration of 10 μ M A β 42 plus 10, 30, 100, and 300 μ M α -TOC, α -T3, and γ -T3, and incubated the mixtures at 37 °C for 5, 10, and 22 h.

2.3. Thioflavin T fluorescence assay

We conducted the ThT fluorescence assay as described previously [6]. We measured the fluorescence intensity in 96-well black plates (Greiner Bio-one, Frickenhausen, Germany) using an Infinite M200 microplate reader (Tecan, Grödig, Austria) at excitation and emission wavelengths of 450 nm and 482 nm, respectively. As a control, we mixed ThT with PBS containing only α -TOC, α -T3, or γ -T3. The A β 42-specific fluorescence was calculated by subtracting the fluorescence intensity of the control solution. Each measurement was performed in duplicate. Data represent the means of three independent experiments.

2.4. Scanning electron microscopy (SEM) imaging

We observed the effect of α -TOC, α -T3, and γ -T3 on A β 42 aggregation and disaggregation with SEM imaging. We carried out sample preparation according to a previous study with modification [10]. Briefly, we spotted the reaction mixture onto a 150 mesh Formvar-coated nickel grid (Electron Microscopy Sciences, Hatfield, PA, USA) and dried for 20 min at room temperature. Then, we displaced the sample with 2.5% v/v glutaraldehyde in water for 5 min. We then washed the grid by dipping it in water 5 times, repeating the washing step 3 times. Next, we stained the grid with 2% filtered uranyl acetate in water for 30 s, further washed it 3 times in water, and allowed it to dry at room temperature. We observed samples using a field emission SEM (JEOL JSM-7505FA; JEOL, Peabody, MA, USA) at 25 kV. We selected the images of SEM randomly from the 150 mesh Formvar-coated nickel grid that was used to place the reaction mixtures, at a magnification of 25000X.

2.5. Photo-induced cross-linking of unmodified protein (PICUP) assay

We conducted the PICUP assay as described in a previous study [6]. Briefly, we mixed 50 μ M A β 40, A β 42 peptides or

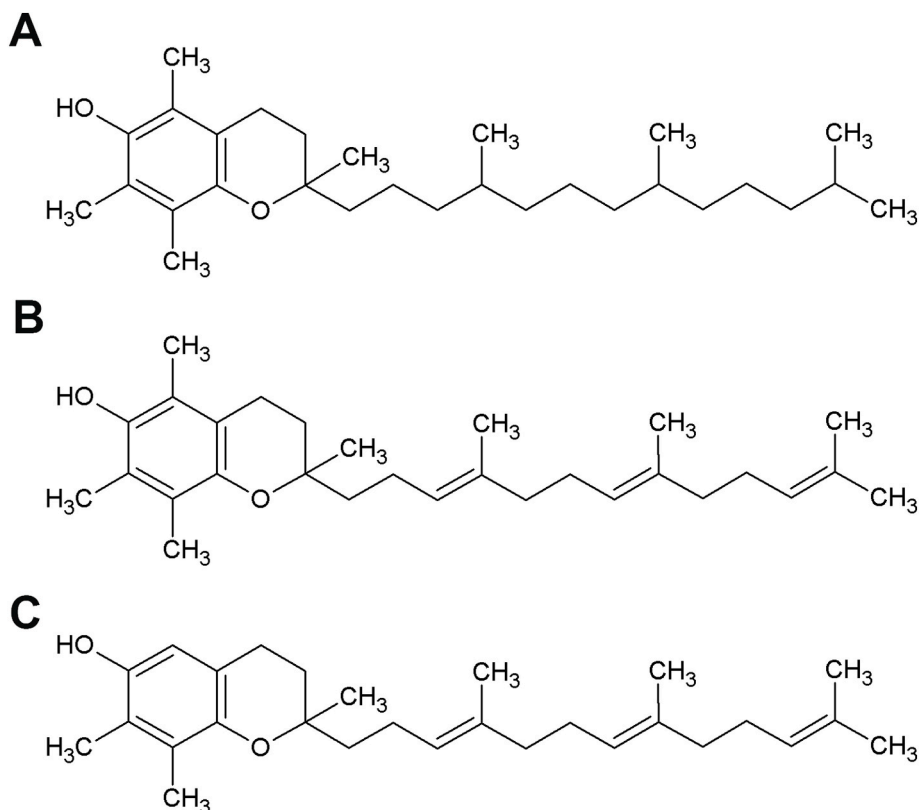


Fig. 1. Structure of tocopherol and tocotrienols: (A) α -tocopherol structure with no double bond at the side chain; (B) α -tocotrienol, and (C) γ -tocotrienol structures with three double bonds at the side chain.

glutathione-S-transferase (GST; Sigma-Aldrich, St. Louis, MO, USA), 2 mM tris (2,2'-bipyridyl) dichlororuthenium (II), and 40 mM ammonium persulfate with α -TOC, α -T3, and γ -T3 at a 1:1 ratio. Immediately, we cross-linked the mixture by PICUP. We subjected the samples to SDS-polyacrylamide gel electrophoresis under reducing conditions with 15%–20% Tricine gel (SuperSep Ace; Wako) and visualized the protein by silver staining with a SilverQuest Staining Kit (Invitrogen, California, USA).

2.6. Statistical analysis

We performed statistical analysis using Graphpad Prism 7 (GraphPad Software; La Jolla, CA, USA). We present data as mean \pm standard error of the mean (S.E.M.). We compared group means by one-way analysis of variance followed by the Bonferroni post hoc test for multiple comparisons.

3. Results

3.1. Effect of α -TOC, α -T3, and γ -T3 on A β 42 aggregation

We performed a ThT assay to determine the effect of α -TOC, α -T3, and γ -T3 on A β 42 aggregation. We incubated 10- μ M A β 42 with 10, 30, 100, and 300 μ M α -TOC, α -T3, or γ -T3 at 37 °C for 5 h, and then carried out the ThT fluorescence measurement. We regarded the average of the ThT fluorescence intensity in A β 42 without compound as 100%

(Fig. 2A–D). In a mixture of A β 42 with 300 μ M α -TOC, we noted a reduction of about 30% in the fluorescence percentage compared to that found in A β 42 without compound. However, at 10 μ M, the fluorescence percentage in α -T3 started to decrease significantly by about 20%, holding its significance at 30 μ M, and at 100 μ M and 300 μ M concentrations, decreased further to about 30% that of A β 42 without compound. Compared to A β 42 without compound, γ -T3 showed a significant decrease at 10 μ M and 300 μ M. Furthermore, the fluorescence percentage of 10 μ M γ -T3 decreased significantly by about 20%–30%, compared to that of α -TOC. We also investigated the effect of α -TOC, α -T3, and γ -T3 on A β 42 aggregation at different incubation times (Fig. 2E–H). We performed ThT fluorescence measurement directly after mixing 30 μ M α -TOC, α -T3, or γ -T3 with 10 μ M A β 42 (Fig. 2E). In the absence of α -TOC, α -T3, or γ -T3, the relative fluorescence intensity of ThT in 10 μ M A β 42 increased progressively (Fig. 2F–H). However, we observed a significant reduction in the relative fluorescence intensity of ThT in A β 42 in the presence, individually, of 30 μ M α -TOC, α -T3, or γ -T3 compared to that found in A β 42 without compound. At 10 and 24 h of incubation time, α -TOC reduced the relative fluorescence intensity. However, at 5, 10, and 24 h of incubation, α -T3 and γ -T3 significantly reduced the relative fluorescence intensity of ThT in A β 42. We chose an incubation time of 5 h during which to assess the effect of different concentrations, individually, of α -TOC, α -T3, and γ -T3 on A β 42 aggregation, as above.

Next, we observed the effects, individually, of α -TOC, α -T3, and γ -T3 on A β 42 aggregation with scanning electron microscopy (SEM) imaging.

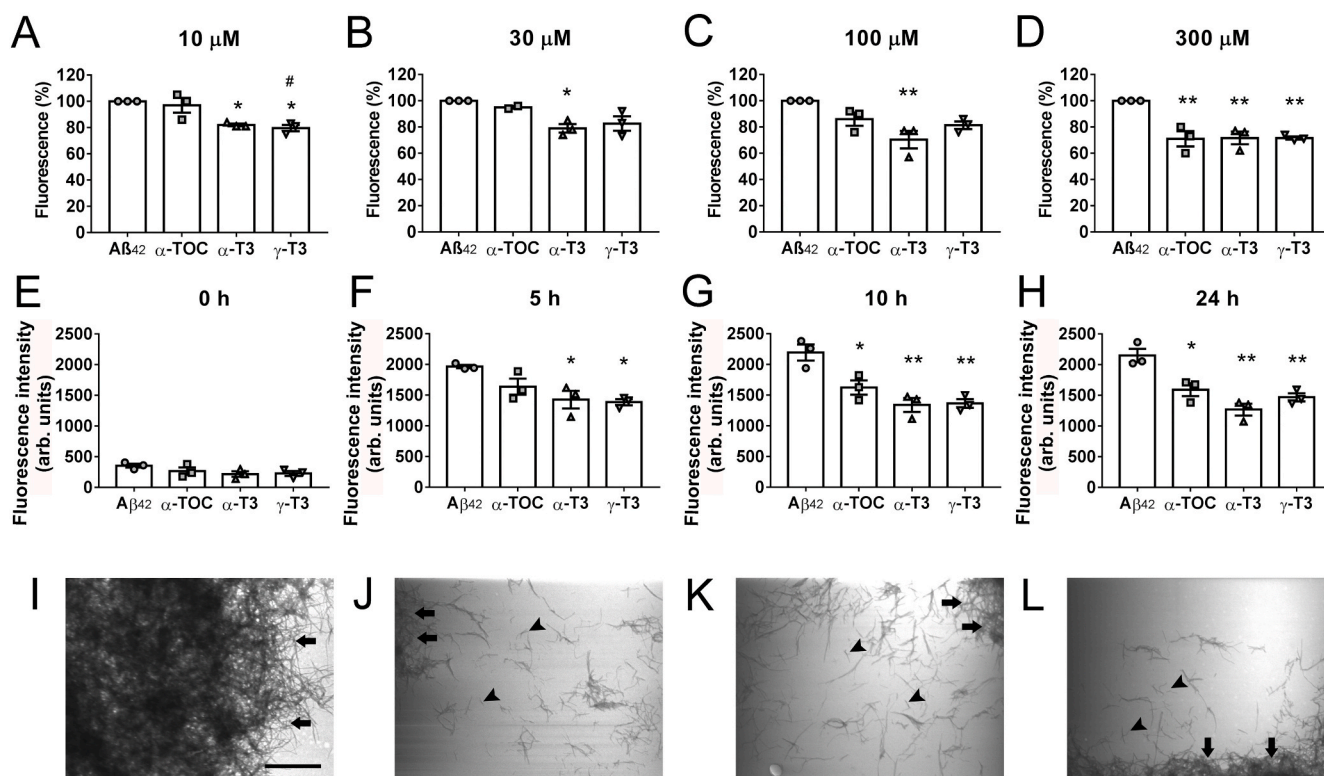


Fig. 2. Effect of α -TOC, α -T3, and γ -T3 on A β 42 aggregation. (A–D) We mixed a final concentration of 10 μ M A β 42 samples with 10, 30, 100, or 300 μ M α -TOC, α -T3, or γ -T3, incubated at 37 °C for 5 h before performing a thioflavin T (ThT) assay. (A) At 10 μ M α -T3 and γ -T3 we observed about 20% reduction in the fluorescence percentage compared to that in A β 42 incubated without compound. We found a significant difference in the fluorescence percentage reduction of γ -T3 and that of α -TOC. (B, C) α -T3 at 30 and 100 μ M significantly reduced the fluorescence percentage by about 20%–30%. (D) α -TOC, α -T3, and γ -T3 significantly reduced the fluorescence percentage compared with that in A β 42 incubated without compound. (E–H) We incubated A β 42 at 37 °C with α -TOC, α -T3, and γ -T3, each at a final concentration of 10 μ M and 30 μ M respectively, and performed the ThT assay at 0, 5, 10, and 24 h. (E) We detected no difference in the relative fluorescence intensity at 0 h, (F) a significant difference for α -T3 and γ -T3 incubated at 5 h, (G, H) and a reduction in the relative fluorescence intensity for α -TOC, α -T3, and γ -T3 at 10 and 24 h of incubation time. We present data as mean \pm S.E.M. Our results were significant at * p < 0.05, ** p < 0.01 versus A β 42 incubated without compound; and # p < 0.05 versus α -TOC. Electron microscopic images of A β 42 incubated with and without α -TOC, α -T3, and γ -T3. (I) Ten-micromolar A β 42 without compound incubated at 37 °C for 24 h. Ten-micromolar A β 42 + 30 μ M (J) α -TOC, (K) α -T3, and (L) γ -T3 incubated at 37 °C for 24 h. Arrows and arrowheads indicate A β fibrils and their sheared fragments, respectively. Scale bar: 1 μ m.

For 10- μM A β 42 incubated without α -TOC, α -T3, or γ -T3 at 37 °C for 5 h, we observed numerous fibrils (Fig. 2I). We made a similar observation (arrow) for 10 μM A β 42 incubated with 30 μM α -TOC (Fig. 2J), α -T3 (Fig. 2K), or γ -T3 (Fig. 2L). However, we observed many short and sheared fragments (arrowhead) in α -TOC, α -T3, and γ -T3 mixtures compared to A β 42 without compound.

3.2. Effect of α -TOC, α -T3, and γ -T3 on disaggregation of preformed A β 42 fibrils

We determined A β 42 fibrillization by incubation of 20 μM A β 42 at 37 °C and performed a ThT assay at 0, 1, 3, 8, 13, and 24 h (Fig. 3A). We noted maximum measurements of ThT fluorescence intensity at 3 h of incubation, at which point the measurement remained consistent at a plateau until 24 h. We used 20- μM A β 42 incubated for 3 h to determine the effect, individually of α -TOC, α -T3, and γ -T3 on A β 42 disaggregation. We mixed α -TOC, α -T3, and γ -T3 at 10, 30, 100, and 300 μM with

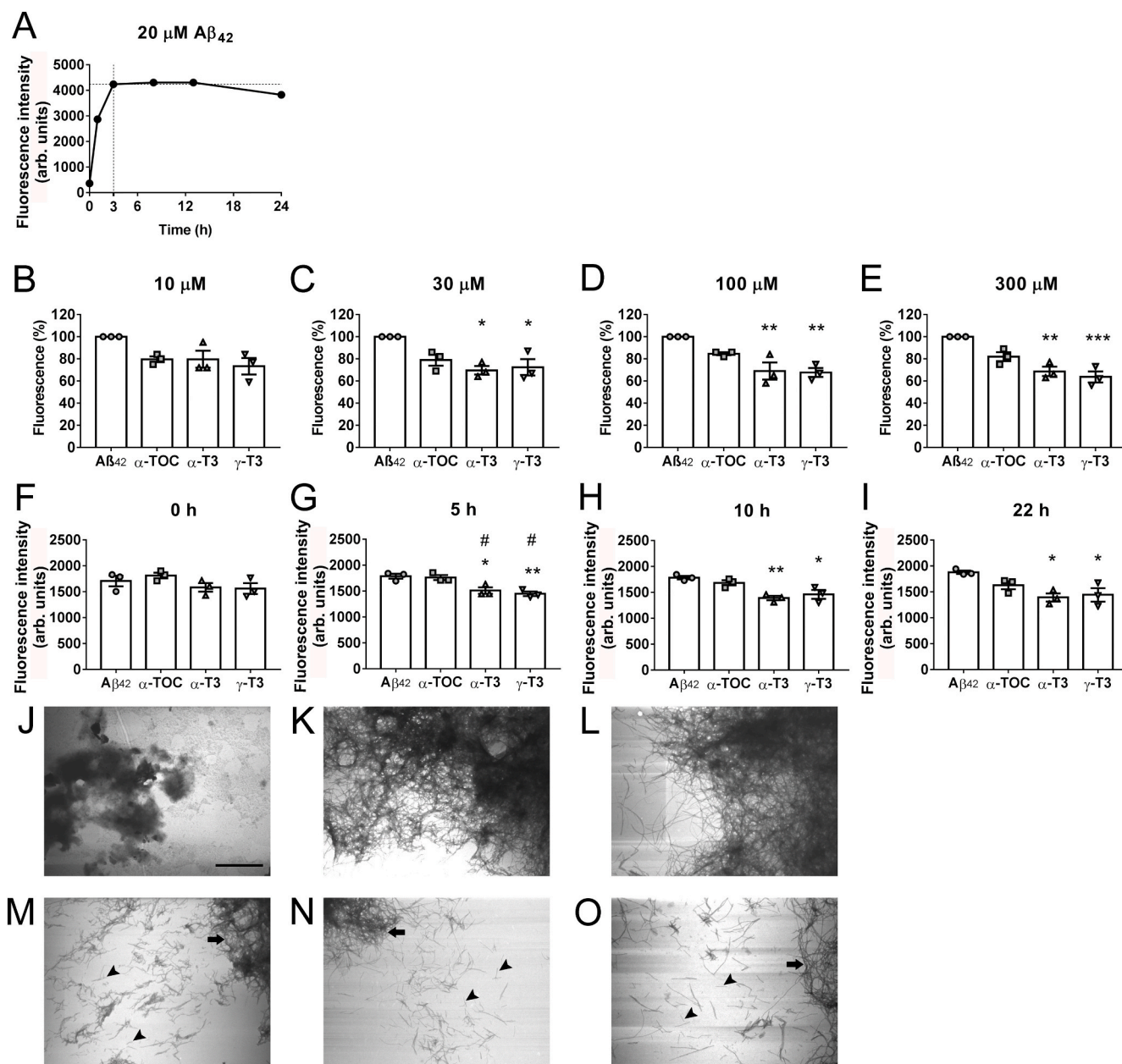


Fig. 3. Effect of α -TOC, α -T3, and γ -T3 on disaggregation of preformed A β 42 fibrils. (A) We incubated 20 μM A β 42 at 37 °C and monitored fibrillization with ThT assay at 0, 1, 3, 8, 13, and 24 h. (B–E) We incubated A β 42 with α -TOC, α -T3, and γ -T3 for 5 h and carried out a relative ThT fluorescence intensity measurement. We found that α -T3 and γ -T3—but not α -TOC—significantly reduced the fluorescence percentage by about 30% compared to the reduction achieved after incubation of A β 42 without compound. (F–I) We incubated A β 42 with 30 μM α -TOC, α -T3, and γ -T3 and performed the relative ThT fluorescence intensity measurement at 0, 5, 10, and 22 h. α -T3 and γ -T3—but not α TOC—significantly decreased the relative ThT fluorescence intensity, compared to that for A β 42 without compound. We present data as mean \pm S.E.M, with significance at * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$ versus A β 42 incubated without compound; and # $p < 0.05$ versus α -TOC. Electron microscopic images of A β 42 fibrils incubated with and without α -TOC, α -T3, and γ -T3. We incubated 20 μM A β 42 at 37 °C for (J) 0 h, (K) 3 h, and (L) 25 h. At 3 h of A β 42 incubation, we added 30 μM (M) α -TOC, (N) α -T3, and (O) γ -T3 and further incubated it for 22 h. We observed distinct A β 42 fibrils (arrow) and also many short, sheared fragments (arrowheads). Scale bar: 1 μm .

A β 42 fibrils (at a final concentration of 10 μ M) and further incubated them at 37 $^{\circ}$ C for 5 h before performing the ThT measurement. We regarded the average ThT fluorescence intensity in A β 42 without compound as 100% (Fig. 3B–E). We did not detect a significant decrease in the fluorescence percentage in α -TOC incubated with A β 42 compared to A β 42 incubated without compound. However, we observed a significant reduction of about 30% in the fluorescence percentage of α -T3 and γ -T3 incubated with A β 42 at 30 μ M, further reduced at 100 μ M, consistent at 300 μ M for α -T3, and further reduced at 300 μ M for γ -T3, compared to that observed for A β 42 incubated without compound. We further investigated the effect of α -TOC, α -T3, and γ -T3 on A β 42 disaggregation at different incubation times (Fig. 3F–I). We found no difference in the relative fluorescence intensity of ThT in A β 42 with or without compound (Fig. 3F). This indicated that the compounds showed no effect to the binding capability of ThT. We mixed 30- μ M α -TOC, α -T3, and γ -T3 with 10 μ M A β 42 fibrils, and conducted ThT measurements before (0 h) and after incubation at 37 $^{\circ}$ C for 5, 10, and 22 h. At 0 h, we observed no difference in ThT relative fluorescence intensity in A β 42 incubated with or without compounds. The relative fluorescence intensity in A β 42 incubated without compound remained constant throughout the incubation periods. We found the relative fluorescence intensity of A β 42 with α -T3 and γ -T3, on the other hand, to decrease at 5, 10, and 22 h incubation. Conversely, we did not detect a decrease in relative fluorescence intensity for α -TOC.

Next, we observed the mixtures with SEM to verify the effect of α -TOC, α -T3, and γ -T3 on A β 42 disaggregation. We prepared 20- μ M of A β 42 and subjected the sample to SEM imaging before and after incubation at 37 $^{\circ}$ C. At 3 h of incubation, we observed distinct fibril morphologies as compared to those at 0 h (Fig. 3J and K). We made a similar observation for A β 42 incubated without compound for another 22 h (Fig. 3L). We also found fibril morphologies in A β 42 incubated with α -TOC, α -T3, and γ -T3 (arrows; Fig. 3M – O); however, we distinguished many short and sheared fragments (arrowhead) from A β 42 incubated without compound (Fig. 3L).

3.3. Effect of α -TOC, α -T3, and γ -T3 on PICUP-Induced A β oligomers

We investigated the effect of α -TOC, α -T3, and γ -T3 on A β oligomerization by PICUP assay. In Fig. 4A we show the uncross-linked mixtures of 25 μ M A β 40 samples appearing as one band representing the monomeric form of A β 40. The cross-linked mixtures of 25 μ M A β 40 without compound (control) resulted in the formation of dimers and trimers. A cross-linked mixture containing 25 μ M A β 40 with 30, 100, or 300 μ M of α -TOC or α -T3 did not affect oligomer formations. However, cross-linked mixtures of 25 μ M A β 40 with 30 or 100 μ M of γ -T3 showed a slight reduction in trimer formation. Also, a 300 μ M γ -T3 mixture with 25 μ M A β 40 totally inhibited oligomerization. Similarly, cross-linked mixtures containing 25 μ M A β 42 with 30 or 100 μ M of γ -T3 reduced the formation of pentamers, as observed in Fig. 4B. Remarkably, we observed complete inhibition in a mixture containing 25 μ M A β 42 with 300 μ M γ -T3. We also conducted the PICUP experiment using a mixture of glutathione-S-transferase (GST) with α -TOC, α -T3, or γ -T3 at different concentrations. In Fig. 4C, we reveal the absence of an inhibitory effect of α -TOC, α -T3, or γ -T3 on GST oligomer formation. This finding thus confirmed the specificity of α -TOC, α -T3, and γ -T3 in the reaction with A β oligomerization.

4. Discussion

In the present study, α -TOC, α -T3, and γ -T3 showed the inhibition of A β aggregation and the promotion of A β disaggregation. The concentration in the present study was chosen based on the study by Yang et al. suggesting 30 and 300 μ M of α -tocopherol quinone, a major derivative of α -TOC, modulate A β aggregation and disaggregation in vitro [10]. The activities of α -TOC and γ -T3 appeared at only a very high molecular ratio (30:1), compared with α -tocopherol quinone (3:1) [10] and curcumin derivatives (3:1) [11], suggesting the effects of α -TOC, α -T3, and γ -T3 on A β aggregation and disaggregation are low. This finding suggests the therapeutic effect of TRF on AD pathology in a mouse model of AD we reported in the previous study might be due to multiple effects of TOC and T3s in TRF on not only A β aggregation and disaggregation but also

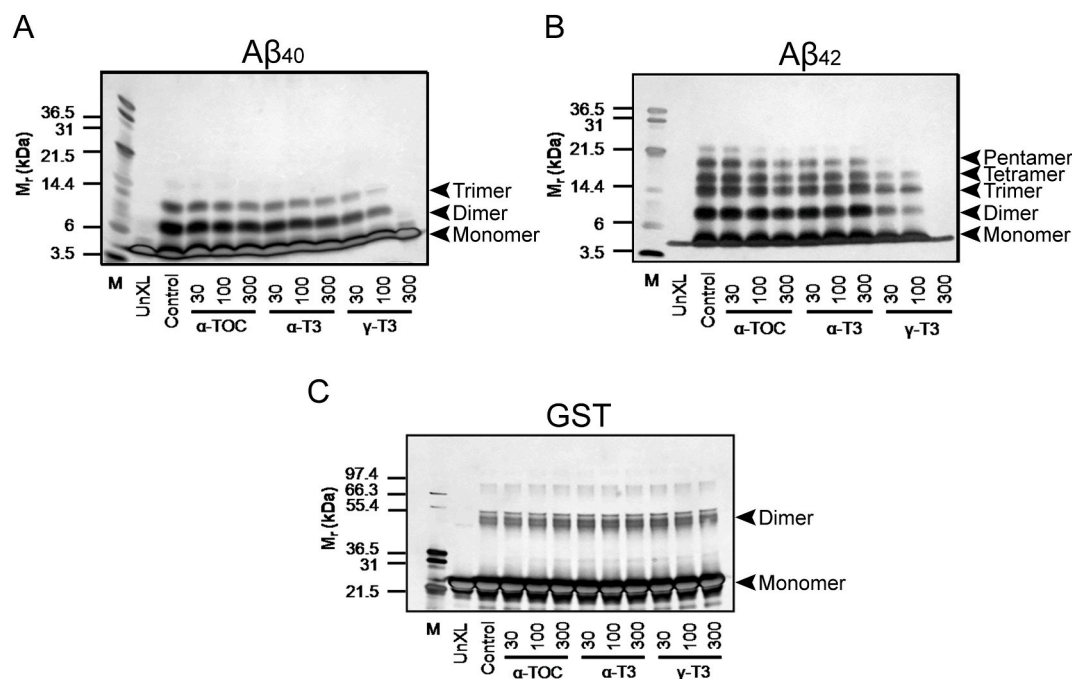


Fig. 4. Effect of α -TOC, α -T3, and γ -T3 on A β 42 oligomerization. We mixed A β 40 (A) and A β 42 (B) peptides with phosphate-buffered saline (control), α -TOC, α -T3, and γ -T3 and cross-linked them in a PICUP assay. We subjected the samples to gel electrophoresis and visualized them by silver staining. While α -TOC and α -T3 showed no effects on A β oligomer formation, γ -T3 reduced oligomer formation of A β 40 and A β 42 in a dose-dependent manner. Neither α -TOC, α -T3, nor γ -T3 had any effect on GST oligomer formation (C). M: marker, UnXL: uncross-linked A β peptides prepared without light exposure.

others such as anti-oxidative stress, anti-inflammatory, and neuro-protection [8]. We speculate that these compounds reduced A β aggregation by directly binding to A β peptides and interfering with the structural conversion on the amyloid species. Previous studies using the other typical organic A β inhibitors such as curcumin and resveratrol postulated the capability of polyphenols to inhibit A β aggregation via the presence of aromatic structures [12,13]. Several studies have reported the significant role of the aromatic interactions in amyloid formation, as well as the self-assembly of complex supramolecular structures [14,15]. Since both tocopherol and tocotrienol comprise the aromatic ring in their structures, α -TOC, α -T3, and γ -T3 are likely to prevent the growth of A β aggregates via the interaction of these compounds with aromatic residues of A β to form π - π stacking arrangements between them.

We found that only α -T3 and γ -T3—but importantly, not α -TOC—were able to disaggregate preformed A β 42 fibrils. This is in agreement with previous studies by Yatin et al. and Yang et al. demonstrating the inability of α -TOC at 50 μ M and 300 μ M, respectively, to inhibit A β fibril formation [10,16]. However, the effect of tocotrienol in modulating A β fibril formation was not investigated in these studies. To our knowledge, the present study is the first to report the direct effect of individual tocotrienol analogs (α -T3 and γ -T3) on A β aggregation and fibril formation in vitro. Vitamin E includes two groups of fat-soluble compounds—namely, tocopherol and tocotrienol, both of which share structural similarities which can be viewed as comprising a chroman head with two rings (one phenolic and one heterocyclic) and a phytol tail. The presence of three double bonds at the C-3', C-7', and C-11' positions of the hydrocarbon tail distinguishes tocotrienol from tocopherol. Several lines of evidence suggest that determination of differential biopotencies exhibited by individual vitamin E isomers are influenced by the level of phytol chain saturation and/or chroman ring methylation [17]. We therefore suggest that the chroman head in the structure of vitamin E may contribute to the inhibitory effect on A β aggregation, while the unsaturated side chain may contribute to the disaggregation of A β fibrils.

The present study did not investigate the effectiveness of γ -tocopherol (γ -TOC) to modulate A β aggregation, disaggregation and oligomerization. A previous study by Pahrudin Arrozi et al. revealed the treatment of SH-SY5Y-APP Swe with γ -TOC in vitro reduced A β 42 levels, mitochondrial reactive oxygen species, and elevated ATP level compared to control [18]. Meanwhile, the study of a randomized trial by Morris et al. using postmortem human brains demonstrated the association between concentration of γ -TOC with lower amyloid load and neurofibrillary tangles severity [19]. The study also showed that higher α -TOC levels were associated with increased amyloid load except when the levels of γ -TOC were also high, at which point higher levels of α -TOC were associated with lower amyloid levels, suggesting that γ -TOC was able to modify the association of α -TOC with amyloid load [19]. These findings presented the important roles of γ -TOC in the modulation of amyloid pathology and therefore, future studies should consider the contribution of γ -TOC in AD neuropathology.

The A β oligomer has been considered the most toxic form of A β to inhibit hippocampal long-term potentiation and disrupt synaptic plasticity [2]. It was found to be elevated in the AD brain and the results were correlated with cognitive decline as measured by the Mini-Mental State Examination [20]. Therefore, a promising target for treating AD would be the inhibition of A β oligomerization. Our previous study found that TRF significantly inhibited A β oligomerization in vitro [6]. TRF is a mixture of α -TOC (168.0 mg/g), α -T3 (196.0 mg/g), β -T3 (24.0 mg/g), γ -T3 (255.0 mg/g), and δ -T3 (75.0 mg/g), which contains the highest amount of γ -T3 analog. TRF has been proved to modulate the expression of various proteins involved in the AD pathway—including amyloid beta A4 (APP) protein in the brain [21]—hence, contributing to the improved cognitive function in APP/PS1 mice [22]. A study by Umeda et al. [23] reported that rifampicin at a molar ratio of 4:1 showed complete inhibition of A β oligomer formation in PICUP assay. In the present study, a

1.2:1 and 4:1 M ratio of γ -T3 to A β reduced pentamer oligomer formation, and at a 12:1 M ratio, we observed a complete oligomer inhibition. We therefore identified γ -T3 as the most effective vitamin E compound to inhibit A β oligomerization. Gamma-T3 lacks one methyl group at the C-5' position of the chromanol ring, distinguishing it from the other two compounds (α -TOC and α -T3) used in the study. The absence of the methyl group at the C-5' position of the chromanol ring is thus a key structure in exerting an inhibitory effect on A β oligomerization.

In conclusion, we found that α -TOC reduced A β aggregation at high concentrations. However, α -T3 reduced A β aggregation and also disaggregated preformed fibrils even at low concentrations. Moreover, γ -T3 showed remarkable effects as it reduced A β aggregation, disaggregated preformed fibrils, and also reduced A β oligomerization. Overall, each vitamin E analog showed different effects on A β aggregation, disaggregation, and oligomerization. Findings from the present study may therefore provide a better understanding of the potential role of the tocotrienols in the development of therapeutic agents for AD.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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