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Discovery of a Tamoxifen-Related Compound that Suppresses Glial L-Glutamate Transport Activity without Interaction with Estrogen Receptors

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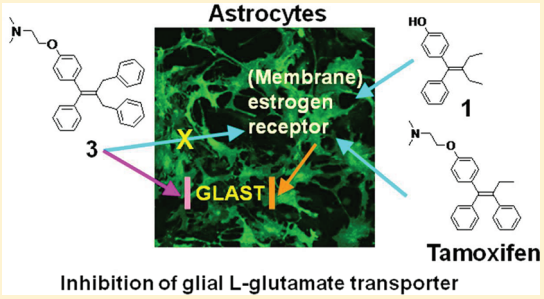
ABSTRACT: We recently found that tamoxifen suppresses L-glutamate transport activity of cultured astrocytes. Here, in an attempt to separate the L-glutamate transporter-inhibitory activity from the estrogen receptor-mediated genomic effects, we synthesized several compounds structurally related to tamoxifen. Among them, we identified two compounds, **1** (YAK01) and **3** (YAK037), which potently inhibited L-glutamate transporter activity. The inhibitory effect of **1** was found to be mediated through estrogen receptors and the mitogen-activated protein kinase (MAPK)/phosphatidylinositol 3-kinase (PI3K) pathway, though **1** showed greatly reduced transactivation activity compared with that of 17β-estradiol. On the other hand, compound **3** exerted its inhibitory effect through an estrogen receptor-independent and MAPK-independent, but PI3K-dependent pathway, and showed no transactivation activity. Compound **3** may represent a new platform for developing novel L-glutamate transporter inhibitors with higher brain transfer rates and reduced adverse effects.



Inhibition of glial L-glutamate transporter

KEYWORDS: *Tamoxifen, astrocyte, L-glutamate transporter, ERα, tetrasubstituted ethylene, nongenomic pathway*

L-Glutamate (L-Glu) is one of the major excitatory neurotransmitters in the central nervous system (CNS), but high concentrations of extracellular L-Glu cause excessive stimulation of L-Glu receptors in the CNS, leading to neurotoxicity.[1,2] Astrocyte L-Glu transporters are the only machinery available to remove L-Glu from extracellular fluid and to maintain a low and nontoxic concentration of L-Glu.[3] Consequently, dysfunction of astrocyte L-Glu transporters is considered to be implicated in the pathology of neurodegenerative conditions.[4] Therefore, exogenous compounds that can regulate the function of L-Glu transporters may provide chemical tools to investigate the regulatory mechanisms of these transporters at the molecular level, and would also be candidate therapeutic agents.

There is growing evidence that estrogen receptor (ER) α, which is a nuclear ER (nER) that mediates genomic effects, can also be translocated to plasma membranes and mediate acute nongenomic effects in some cases. We have clarified that 17β-estradiol (E2) inhibits L-Glu transporters via a nongenomic pathway involving membrane-associated ERα (mERα).[5] Tamoxifen (Tam), a synthetic estrogen analogue that is clinically used in the treatment of breast cancer to block the proliferative action of estrogens,[6] also inhibited astrocyte L-Glu transporters at picomolar concentration, probably through the same nongenomic pathway as E2.[7] Because overexpression of astrocyte L-Glu transporters is often associated with neuropsychiatric disorders,[4] inhibitors of L-Glu transporters may be clinically useful to ameliorate these disorders.[8] However, Tam also acts on genomic pathways involving nuclear estrogen receptors (nERs) α and β, depending on the cell type and promoter context,[9] and so may cause adverse effects including endometrial changes, depression and weight gain.[10,11] Therefore, Tam-inspired compounds that retain the inhibitory effect on L-Glu transporters, but lack the nER-mediated genomic effects, would be useful tools for biological research, as well as candidate therapeutic agents.

Tam is a tetrasubstituted triphenylethylene derivative, in which the four substituents on the olefinic carbon atoms are different. This structural complexity makes the stereospecific synthesis of Tam-related derivatives difficult. We thus focused on Tam-inspired compounds bearing identical substituents on at least one of the olefinic carbon atoms.[12] It is well-known that the *N*,*N*-dimethylaminoethyl substituent on the phenolic oxygen atom and the regiochemistry of the tetrasubstituted

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olefin of Tam are crucial for ER binding activity.[13] So, we considered that more symmetrical derivatives of Tam might show reduced ER-binding ability.

Among our synthesized compounds, we found two, compounds **1** (YAK01) and **3** (YAK037), with potent L-Glu transporter-inhibitory activity. Studies of their mechanisms of action indicated that, unlike Tam, compound **3** acts through an ER-independent and MAPK-independent, but PI3K-dependent pathway and shows no transactivation activity for nERs. We believe this compound may represent a new platform for developing novel L-Glu transporter inhibitors with higher brain transfer rates and reduced adverse effects.

RESULTS AND DISCUSSION

We synthesized several Tam-inspired compounds bearing identical substituents on one carbon atom of the olefin,[12] and found that two of them were potent inhibitors of astrocyte L-Glu transporters. The diethyl-substituted derivative **1** inhibited L-Glu transporters in the picomolar range (62.7 ± 7.48% of control at 1 pM; Figure 2A). The dose−response curve for the inhibitory activity was not linear, but followed an inverted U-shaped curve; however, such a non-monotonic dose dependence is rather common for hormones and their mimetics.[14] On the other hand, when the symmetrical substituent was changed from ethyl to benzyl (**2**), the inhibitory effect was lost (Figure 2B). However, when the phenolic oxygen atom of **1** was substituted with a *N*,*N*-dimethylaminoethyl group (Figure 1C), we found

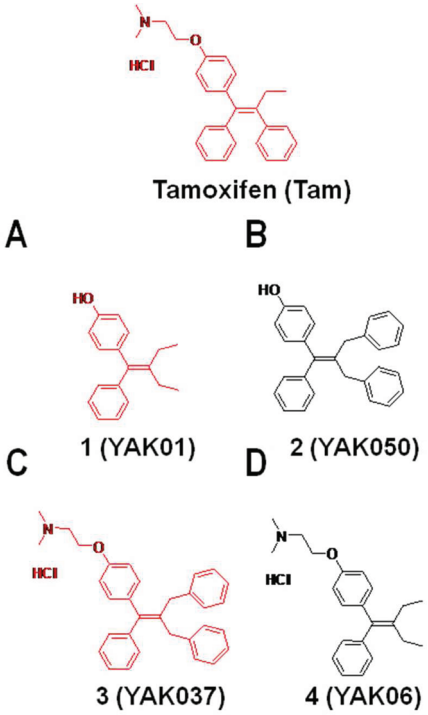

Figure 1. Chemical structures of the newly synthesized tamoxifen-related compounds.

that the resulting compound **3** showed dose-dependent L-Glu transporter inhibition in the picomolar range (63.8 ± 5.49% of control at 1 pM; Figure 2C). The dose-dependency of the effect of **3** suggested that the underlying mechanism might be different from that in the case of **1**. Compound **4** was inactive (Figure 2D).

We next examined the effects of **1** and **3** on cell viability by means of MTT reduction assay and LDH leakage assay, using the same cultured sample. Neither of the compounds was cytotoxic at concentrations below 1 μM (Figure 3), though 100 μM **1** and 10 μM **3** caused severe cell damage. These results exclude the possibility that the L-Glu clearance-inhibitory effects of these compounds at concentrations below 1 μM were caused by cell damage.

In order to confirm the involvement of L-Glu transporters in the inhibition of L-Glu uptake by our compounds, and to rule out the possibility that **1** and **3** act by inducing L-Glu release from astrocytes, we next examined the effect of **1** and **3** on L-Glu clearance when the L-Glu transporter activity was blocked with TBOA, a potent nonselective L-Glu transporter inhibitor (IC_{50}: 48 μM for GLAST/EAAT1, 7 μM for GLT1/EAAT2). We confirmed that application of 1 mM TBOA potently inhibited L-Glu transporter activity; that is, TBOA caused reversible chemical knock-down of L-Glu transporter activity.[7] When either **1** or **3** was coapplied with 1 mM TBOA, these compounds no longer influenced L-Glu clearance (Figure 4), indicating that the actions of these compounds are indeed mediated by L-Glu transporters, and do not involve L-Glu release from astrocytes.

Our cultured astrocytes predominantly expressed ERα, and little or no expression of ERβ was detected.[5] Tam is known to be a partial agonist of ERs,[9] raising the possibility that the compounds exerted their inhibitory effects via interaction with ERα. Therefore, we examined the involvement of ERα by coapplication of ICI182,780, a high-affinity antagonist of ERs. ICI182,780 dose-dependently blocked the inhibition of L-Glu uptake caused by **1** (Figure 5A) at 0.01, 0.1, and 1 μM, at which the effects of Tam were reported to be completely suppressed.[7] In contrast, ICI182,780 had no effect on the inhibition by **3** (Figure 5B), suggesting that the mechanism of the inhibition by **3** is independent of ERs. We further examined the signal transduction pathways mediating the effects of **1** and **3**. When coapplied with U0126, which inhibits mitogen-activated protein kinase/extracellular signal-regulated kinase 1 (MEK1, IC50: 70 nM) and MEK2 (IC50: 60 nM), the inhibitory effect by **1** was blocked, whereas that of **3** was not (Figure 6A). On the other hand, when coapplied with LY294002, a specific phosphoinositide 3-kinase (PI3K) inhibitor (IC50: 70 nM), the inhibitory effects of both compounds were completely blocked (Figure 6B). These results suggest that PI3K is a common mediator of the effects of both compounds, whereas mitogen-activated protein kinase (MAPK) is involved only in the mechanism of inhibition by **1**.

Finally we examined the ER-agonist potency of **1** and **3**, i.e., the transcriptional effects of these compounds via human ERα and ERβ, using HEK293/hERα and HEK293/hERβ reporter cells (Figure 7). Compound **1** showed agonist activity in both of 293/hERα and 293/hERβ reporter cells, though the binding affinities were much weaker than that of E2. The EC50 values of **1** for ERα and ERβ are 30.8 nM and 10.4 nM, respectively (1.25 nM and 0.864 nM, respectively, for E2). The relative agonist activity of **1** was 66.8% of that of E2 in HEK293/hERα and 122.0% of that of E2 in HEK293/hERβ. Strikingly, **3** showed no agonist potency for ERα or ERβ. These findings strongly suggest that **3** can inhibit L-Glu transporters without interaction with ERs.

In this study, we examined the potential of Tam-related compounds to inhibit GLAST/EAAT1 and GLT1/EAAT2, which are major astrocytic L-Glu transporters in the rat

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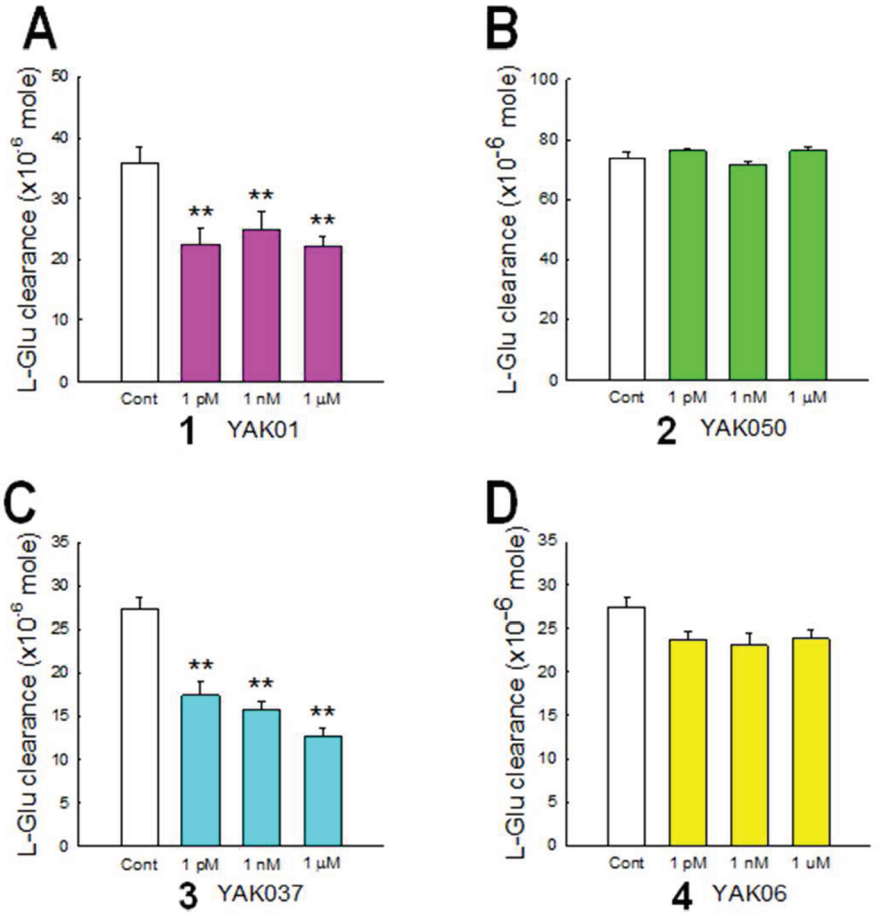

Figure 2. Compounds **1** and **3** inhibited L-Glu clearance in cultured astrocytes. The open column shows the control clearance, and colored columns show the clearance in the presence of various concentrations of compounds **1** (A), **2** (B), **3** (C), and **4** (D). $^{**}p < 0.01$ vs control group ($N = 6$), Tukey's test following ANOVA.

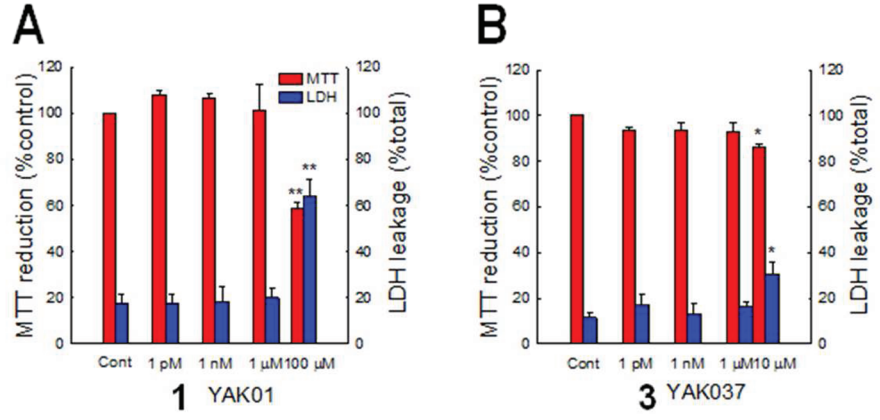

Figure 3. Effects of compounds **1** and **3** on cell viability. The results of MTT reduction and LDH leakage assays of **1** (A) and **3** (B) are shown. $^{*}p < 0.05$, $^{**}p < 0.01$ vs control group ($N = 6$), Tukey's test following ANOVA.

forebrain. Although GLT-1 is the main regulator of synaptically released L-Glu in vivo, the predominant subtype changes to GLAST in cultured astrocytes, possibly owing to the lack of interaction of astrocytes with neurons.[15] We confirmed that GLAST is the main functional L-Glu transporter in our primary-cultured astrocytes by Western blotting and pharmacological experiments (data not shown), in accordance with a previous report.[16] Therefore, the effects of the compounds observed here can be interpreted as being due to modulation of GLAST functional activity.

There is growing evidence that ERα, which is a nER that mediates genomic effects, can also be translocated to plasma membranes and mediate acute nongenomic effects in some cases. Transfection of CHO cells with nERs was reported to result in ER expression in both nuclei and membranes.[17] ERs on the plasma membranes of tumor cells were demonstrated to be structurally similar to nERs.[18] Further, mERα activated metabotropic glutamate receptor 5 (mGluR5) in striatal neurons in the CNS.[19] In our previous study, we clarified that the predominant ER subtype in cultured astrocytes was ERα, and

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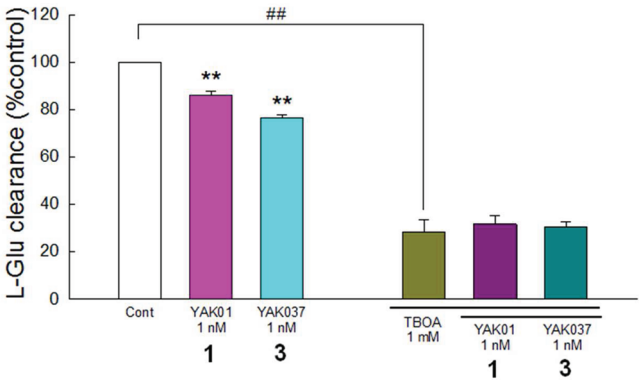

Figure 4. Compounds **1** and **3** suppressed L-Glu clearance in astrocyte culture by decreasing the functional activity of L-Glu transporter. L-Glu clearance in the presence and absence of compounds **1** and **3** is shown, together with their effects in the copresence of the potent nonselective L-Glu transporter inhibitor TBOA. $^{**}p < 0.01$ vs control group ($N = 6$), Tukey's test following ANOVA.

estrogens (such as E2 and Tam) inhibited L-Glu transporter activity via the activation of mERα.[5] We found that the effects of **1** were blocked by ICI182,780, suggesting an interaction of **1** with ERα. In addition, our pharmacological experiments showed that activation of both of MAPK and PI3K is necessary for the L-Glu transporter-inhibitory activity of **1**. There are many reports indicating that nongenomic effects involving mERα are mediated via MAPK[19−21] and PI3K.[20,22] Taken together, the effects of **1** may be mediated by mERα in a similar manner to E2 and Tam. E2 was reported to activate MAPK via both PI3K-dependent and independent pathways in a single neuron.[20] Whether or not the same signaling pathways also exist in astrocytes is not yet known. It is of interest that other studies have found that estrogens also inhibit dopamine transporter (DAT) through the activation of mERα.[23,24]

On the other hand, the effect of **3** was ER-independent and MAPK-independent, but PI3K-dependent. Our binding assay revealed that **1** binds with ERs, but **3** does not. Based on these results, we propose that the mechanisms of the L-Glu

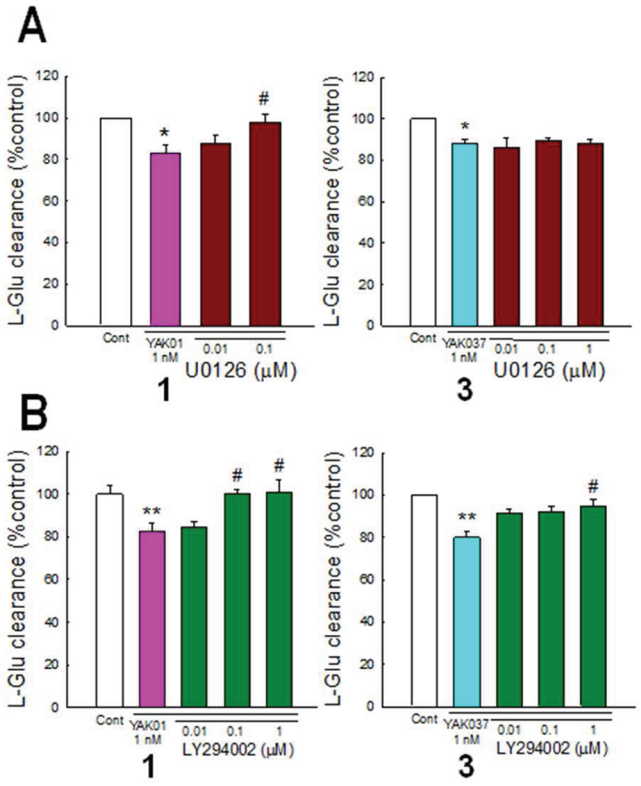

Figure 6. Involvement of MAPK and PI3K in the L-Glu transporter-inhibitory activity of compounds **1** (A) and **3** (B). Effects of compounds **1** (left panels) and **3** (right panels) on L-Glu clearance in the presence and absence of various concentrations of U0126, an inhibitor of MAPK/ERKs (A) or LY294002, a specific inhibitor of PI3K (B). $^{*}P < 0.05$, $^{**}p < 0.01$ vs control group, $\#p < 0.05$ vs compound-treated group ($N = 6$), Tukey's test following ANOVA.

transporter-inhibitory effects of **1** and **3** are different, as illustrated in Figure 8. The effect of **3** was possibly mediated by GPR30, a newly found ER, which is suggested to mediate the rapid nongenomic effects of estrogens.[25,26] In the case of GPR30, ICI182,780 acts as agonist, leading to activation of

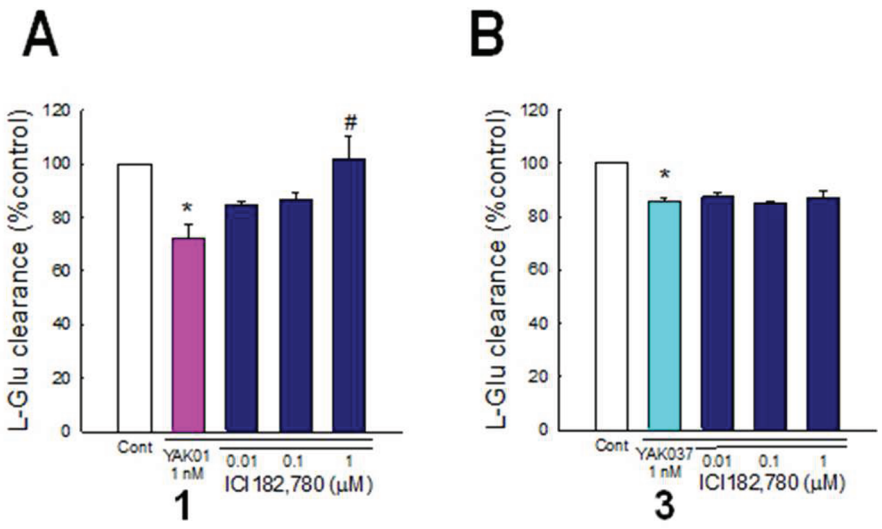

Figure 5. Involvement of ERs in the L-Glu transporter-inhibitory effects of compounds **1** and **3**. Effects of compounds **1** (A) and **3** (B) on L-Glu clearance in the presence and absence of various concentrations of ICI182,780, a high-affinity antagonist of ERs. $^{*}P < 0.05$ vs control group, $\#p < 0.05$ vs compound-treated group ($N = 6$), Tukey's test following ANOVA.

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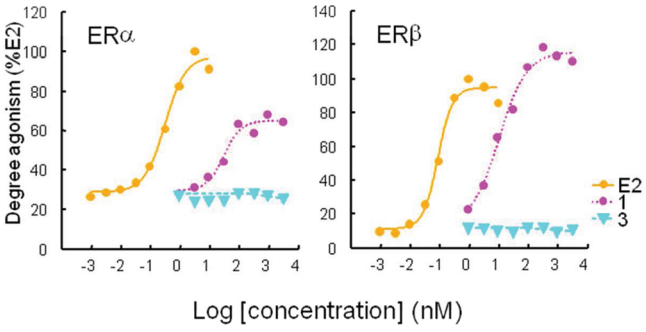

Figure 7. ER agonist potency of compounds **1** and **3** to nERs: dose dependence of binding of compounds **1** and **3** in HEK293/hERα cells (left) or HEK293/hERβ cells (right). Compound 1 showed dose-dependent agonist activity in both of HEK293/hERα cells (left) and HEK293/hERβ cells (right), though 3 showed no agonist potency for ERα or ERβ.

signal transduction pathways in a similar manner to estrogens.[27,28] However, we could not detect any effects of ICI182,780 alone on L-Glu transporter in our experiments (data not shown). In addition, Kuo et al. reported that GPR30 in astrocytes is detected not in the cell membranes but in the smooth endoplasmic reticulum,[29] while the cellular localization of GPR30 has been still controversially argued. In these contexts, GPR30 is an unlikely mediator to block the L-Glu transporters by the action of **3**.

According to Kisanga et al., the concentration of Tam in serum during conventional treatment for breast cancer (1−20 mg daily) is in the range from 20 to 225 nM.[30] Because **3** is more hydrophobic than Tam (the values of clogP for Tam and **3** are 7.56 and 9.70, respectively), it should exhibit greater permeability into the brain. Although other L-Glu transporter inhibitors, mainly L-Glu/aspartate analogues, are known, few of them have high brain transfer rates. Therefore, **3** is expected to be useful for biological research, and is also considered to be a promising candidate or lead compound for pharmacological application.

In conclusion, examination of several Tam-inspired compounds led to the discovery of two compounds that inhibited astrocytic L-Glu transporters at picomolar concentration. The inhibitory activity of compound **1** was mediated through the ER-MAPK/PI3K pathway, like that of Tam, though its transactivation activity was drastically reduced as compared with E2. In contrast, the inhibitory effect of **3** was manifested through an ER-independent and MAPK-independent, but PI3K-dependent pathway, and **3** showed no transactivation activity. These results suggest that **3** may represent a new platform for the development of novel L-Glu transporter inhibitors with higher brain transfer rates and reduced adverse effects.

METHODS

Chemistry. *General Procedures.* All reagents were commercial products and were used without further purification, unless otherwise noted. NMR data were recorded on a JEOL-400 or a Bruker Avance 400 NMR spectrometer (400 MHz for ^{1}H NMR and 100 MHz for ^{13}C NMR). *d*-$CDCl_3$ was used as a solvent, unless otherwise noted. Chemical shifts (δ) are reported in ppm with respect to internal tetramethylsilane (δ = 0 ppm) or undeuterated residual solvent (i.e., $CHCl_3$ (δ = 7.265 ppm)). Coupling constants are given in hertz. Coupling patterns are indicated as follows: m = multiplet, d = doublet, s = singlet, br = broad. High-resolution mass spectrometry (HRMS) was conducted in the electron spray ionization (ESI)-time-of-flight

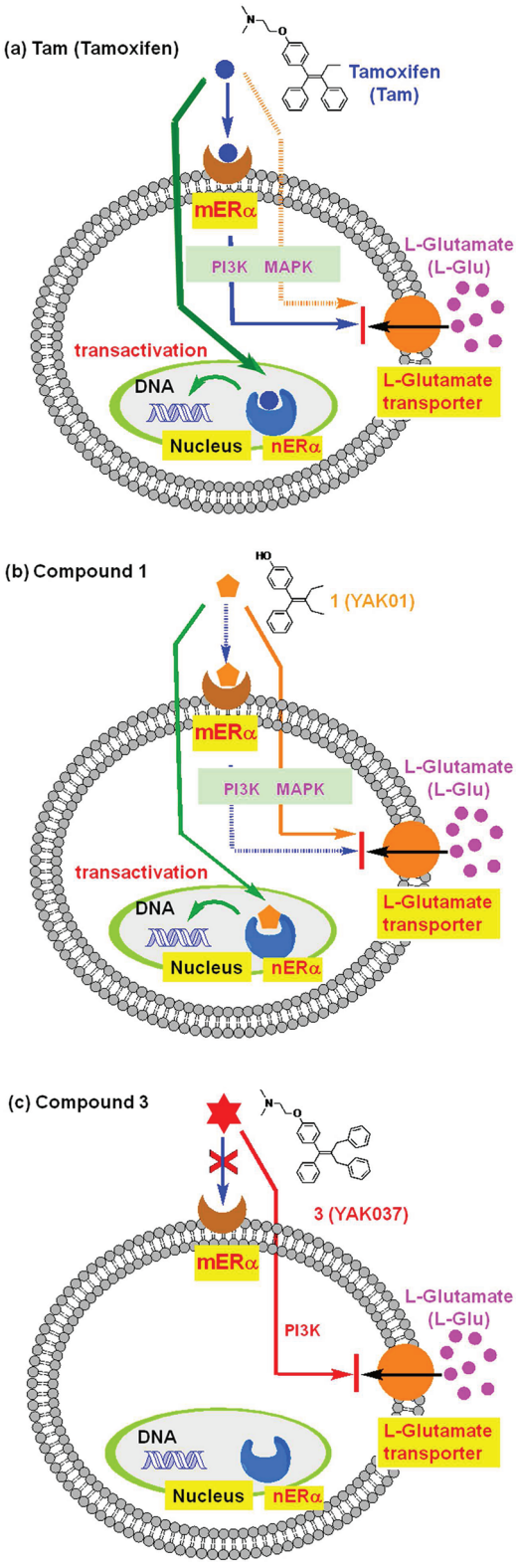

Figure 8. Schematic illustration of the proposed mechanisms of the effects of tamoxifen (a) and compounds **1** (b) and **3** (c).

(TOF) detection mode on a Bruker micrOTOF-05. FAB-MS and high-resolution FAB-MS were obtained on a JMS700-MSTATION (JEOL, Japan). Column chromatography was carried out on silica gel (silica gel 60N (100−210 μm), Kanto Chemicals, Japan). Flash column chromatography was performed on silica gel H (Merck, Germany). Analytical thin-layer chromatography (TLC) was performed on

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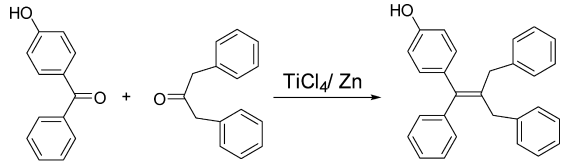
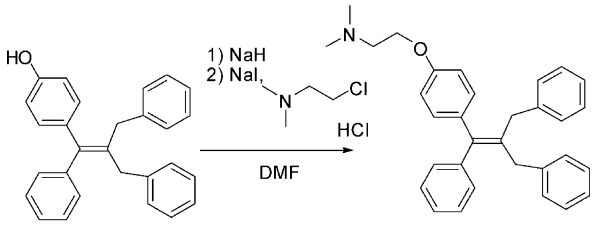
precoated plates of silica gel HF_{254} (Merck, Germany). All the melting points were measured with a Yanaco Micro Melting Point apparatus and are uncorrected. Combustion analyses were carried out in the microanalysis laboratory of this faculty.

Synthesis of Compounds. Compounds **1** and **2** were synthesized from 4-hydroxybenzophenone and butyl-3-one or dibenzylacetone by using $TiCl_4$ in the presence of Zn. Introduction of the *N*,*N*-dimethylaminoethyl moiety at the phenolic hydroxyl group of **1** and **2** was carried out by base treatment, followed by addition of 2-dimethylaminoethyl chloride hydrochloride.

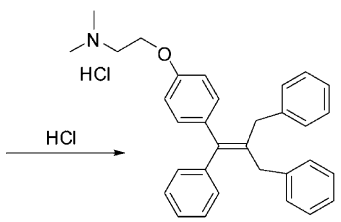


2 (YAK050)

Synthesis of Tamoxifen-Related Compounds. Compound 2 (YAK050). To a suspension of Zn powder (916.6 mg; 6.9 equiv with respect to 4-hydroxybenzophenone) in dry THF (30 mL) in a 200 mL three-necked flask, $TiCl_4$ (0.61 mL, 2.8 equiv) was added dropwise under an argon atmosphere at −20 °C (in an ice-salt bath) over 2 min. The resulting light green-yellow mixture was stirred at −20 °C for 20 min and then the cooling bath was removed. After 20 min, the flask was immersed in a preheated oil bath at 100 °C and refluxed at 100 °C with stirring for 2.5 h. To the resulting deep blue mixture was added in one portion a solution of 4-hydroxybenzophenone (401.3 mg, 2.02 mmol) and dibenzyl ketone (1.2735 g, 3 equiv) in 50 mL of dry THF. The resultant mixture was heated at reflux at 100 °C with stirring for 2 h, then allowed to cool to rt, and poured into 400 mL of 0.5 N aqueous NaOH solution. The whole was extracted with ethyl acetate (500 mL). The organic layer was washed with water, dried over $MgSO_4$ and evaporated to give a pale yellow oil (1.5172 g), which was column-chromatographed (silica gel, acetone/*n*-hexane (1:7)) to give 365.0 mg (48% yield) of the olefin **2** as a white amorphous solid. Mp: 57−60 °C. ^{1}H NMR ($CDCl_3$): δ: 7.287−7.079 (m, 17H), 6.760 (d, 2H, J = 8.8 Hz), 4.792 (s, 1H), 3.413 (s, 2H), 3.377 (s, 2H). ^{13}C NMR ($CDCl_3$): δ: 154.1, 143.0, 140.7, 140.4, 135.8, 135.4, 130.7, 129.4, 128.8, 128.3, 128.3, 128.2, 126.5, 125.9, 115.1, 37.4, 37.2. HRMS (ESI^-): Calcd. for $C_{28}H_{23}O$ ($[M - H]^-$), 375.1754. Found: 375.1744. Anal. Calcd for $C_{28}H_{24}O{\cdot}0.2H_2O$: C, 88.48; H, 6.47; N, 0.00. Found: C, 88.36; H, 6.63; N, 0.00.



2 (YAK050)

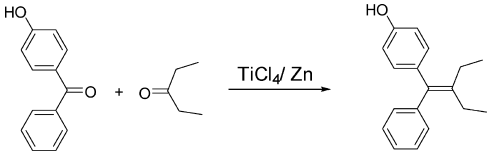


3 (YAK037)

Compound 3 (YAK037). To a suspension of NaH (60%, 42 mg, 1.05 mmol) in DMF (3 mL) at 0 °C was added a solution of the phenol **2** (158.2 mg, 0.420 mmol) in DMF (3 mL). The reaction mixture was stirred for 30 min at 0 °C, and then a solution of 2-dimethylaminoethyl chloride hydrochloride (181.0 mg, 1.256 mmol, 3.0 equiv) and NaI (94.0 mg, 0.627 mmol, 1.5 equiv) in DMF (3 mL) was added. The reaction mixture was stirred at 50 °C for 30 min, and then saturated aqueous NH_4Cl was added to quench the reaction. The mixture was extracted with Et_2O. The organic layer was washed with brine, dried over Na_2SO_4 and evaporated to afford a residue, which was column-chromatographed (ethyl acetate/Et_3N = 100/1) to give the intermediate amine (83.0 mg, 44% yield). The HCl salt of the resultant amine was prepared by repeated addition of a solution of 2 N HCl in Et_2O to a solution of the amine in ethyl acetate, followed by evaporation of the organic solvent to give **3**.

3: White solid. Mp. 169−170 °C. ^{1}H NMR ($CDCl_3$): δ: 13.073 (brs, 1H), 7.306−7.195 (m, 13H), 7.102−7.074 (m, 4H), 6.832 (d, 2H, J = 8.8 Hz), 4.481−4.459 (m, 2H), 3.425−3.390 (m, 6H), 2.893 (s, 6H). ^{13}C NMR ($CDCl_3$) δ: 155.7, 142.8, 140.4, 140.3, 140.2, 136.8, 136.2, 130.9, 129.4, 128.8, 128.7, 128.4, 128.3, 128.3, 126.6, 126.0, 125.9, 114.3, 62.8, 56.5, 43.6, 37.4, 37.2. HRMS (ESI^+, $[M + H]^+$): Calcd. for $C_{32}H_{34}NO$, 448.26349. Found: 448.26092. Anal. Calcd for $C_{32}H_{34}ClNO{\cdot}1/4H_2O$: C, 78.67; H, 7.12; N, 2.87. Found: C, 78.64; H, 7.30; N, 2.87.

Compound 1 (YAK01).



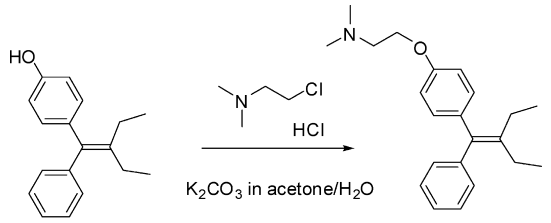
1 (YAK01)

To a suspension of Zn (0.86 g, 13.2 mmol) in 30 mL of dry THF at −5 °C was added dropwise $TiCl_4$ (0.72 mL, 6.6 mmol) under an argon atmosphere. The mixture was heated at reflux for 2 h. A solution of 4-hydroxybenzophenone (341.1 mg, 1.7 mmol) and 3-pentanone (0.50 mL, 5.0 mmol) in 50 mL of dry THF was added in one portion, and heating was continued at reflux for 6 h. Then the reaction mixture was cooled to rt, quenched with 10% aqueous K_2CO_3 (100 mL) and extracted with ethyl acetate (3 × 80 mL). The combined organic phase was washed with brine (50 mL), dried over Na_2SO_4, and evaporated to give a residue, which was flash column-chromatographed (3:1 hexane/ethyl acetate) to afford **1** (383.4 mg, 88.3%) as a white solid.

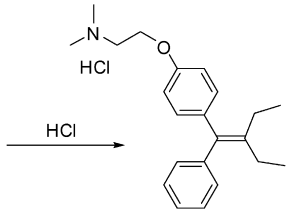
1: Mp. 76.0−76.5 °C (colorless needles, recrystallized from *n*-hexane). ^{1}H NMR ($CDCl_3$) δ: 7.261 (2H, t, J = 8.0 Hz), 7.173 (1H, d, J = 7.2 Hz), 7.128 (2H, d, J = 7.6 Hz), 7.009 (2H, d, J = 8.8 Hz), 6.726 (2H, d, J = 8.8 Hz), 4.763 (1H, s), 2.152 (2H, quartet, J = 7.6 Hz), 2.115 (2H, quartet, J = 6.0 Hz), 1.007 (3H, t, J = 7.6 Hz), 0.994 (3H, t, J = 7.6 Hz). ^{13}C NMR ($CDCl_3$) δ: 153.7, 143.7, 142.0, 136.5, 136.2, 130.5, 129.2, 127.9, 125.9, 114.8, 24.4, 24.3, 13.3. HRMS (ESI^-, $[M - H]^-$): Calcd. for $C_{18}H_{19}O^-$, 251.14414. Found: 251.14730. HRMS (FAB-MS, $[M]^+$) Calcd. for $C_{18}H_{20}O$, 252.1514. Found: 252.1528. Anal. Calcd. for $C_{18}H_{20}O$: C, 85.67; H, 7.99; N, 0.00. Found: C, 85.38; H, 8.13; N, 0.00.

Compound 4 (YAK06).

2-Dimethylaminoethyl chloride hydrochloride (282.4 mg, 2.0 mmol) and K_2CO_3 (1.5734 g, 11.4 mmol) were stirred in acetone/H_2O (18 mL/2 mL) at 0 °C for 30 min, then compound **1** (139.1 mg, 0.55 mmol) and K_2CO_3 (421.1 mg, 3.1 mmol) were added, and the whole was heated at reflux for 24 h, then cooled to rt. Inorganic materials were removed by filtration, and the filtrate was evaporated. The residue was flash column-chromatographed (100:1 ethyl acetate/Et_3N) to afford the amine as a white solid (88.0 mg). To a solution of the amine in ethyl acetate, a solution of HCl in ether was added to give a precipitate, which was collected and recrystallized from ethanol/ethyl acetate to give **4** (95.0 mg, 48%) as a white powder. **4**: Mp. 129.5−130.2 °C. ^{1}H NMR ($CDCl_3$) δ 726−6.90 (9H, m), 4.07 (2H, t, J = 6.0 Hz), 2.75 (2H, t, J = 6.0 Hz), 2.40 (6H, s), 2.15 (4H, d, J = 7.2 Hz), 1.00 (6H, t, J = 7.2 Hz). HRMS (FAB-MS, [M-Cl]$^+$): Calcd. for $C_{22}H_{30}NO^+$: 324.2322. Found: 324.2321.



1 (YAK01)



4 (YAK06)

Biology. All procedures using live animals in this study were conducted in accordance with the guidelines of the National Institute of Health Sciences, Japan.

Materials. Dulbecco's modified Eagle's medium (DMEM) and fetal bovine serum (FBS) were purchased from GIBCO (CA, USA). Glutamate dehydrogenase (GLD) was purchased from Roche (Mannheim, Germany). β-Nicotinamide adenine dinucleotide (βNAD), 3-(4,5-dimethyl-2-thiazolyl)-2,5-diphenyl-2H-tetrazolium bromide (MTT), 1-methoxy-5-methylphenazinium methyl sulfate (MPMS), lactate lithium salt and LY294002 were purchased from Sigma (MO, USA). DL-threo-β-benzyloxyaspartic acid (TBOA) and ICI182,780 were purchased from Tocris (MO, USA). U0126 was purchased from Promega (WI, USA). Assay kits for hormonal effects on HEK293/hERα and HEK293/hERβ reporter cells were purchased from Clontech (CA, USA).

Cell Culture. Primary cultures of astrocytes were prepared from the cerebral cortices of 3-day-old neonates of Wistar rats, as described previously.[31] Briefly, dissociated cortical cells were suspended in modified DMEM containing 30 mM glucose, 2 mM glutamine, 1 mM pyruvate and 10% FBS, and plated on uncoated 75 cm^2 flasks at the density of 600 000 cells/cm^2. A monolayer of type I astrocytes was obtained 12−14 days after plating. Nonastrocytes such as microglia were detached from the flasks by shaking and removed by changing the medium. Astrocytes in the flasks were dissociated by trypsinization, reseeded on uncoated 96-well microtiter plates at 20 000 cells/cm^2, and incubated until the cells became confluent (approximately 9−10 days after reseeding). In this culture, >98% of the cells were identified as type I astrocytes on the basis of positivity for GFAP and flattened, polygonal appearance.

Measurement of Extracellular L-Glu Concentration. Extracellular L-Glu concentration was measured by means of a colorimetric method according to Abe et al.[32] Briefly, 50 μL of culture supernatant was transferred to each well of a 96-well microtiter plate and mixed with 50 μL of substrate mixture consisting of 20 U/mL GLD, 2.5 mg/mL β-NAD, 0.25 mg/mL MTT, 100 μM MPMS and 0.1% (v/v) Triton X-100 in 0.2 M Tris-HCl buffer (pH 8.2). After 10 min incubation at 37 °C, the reaction was stopped by adding 100 μL of solution containing 50% (v/v) dimethylformamide and 20% (wt/vol) SDS (pH 4.7). In this reaction, MTT (yellow) is converted into MTT formazan (purple) in proportion to the L-Glu concentration. The amount of MTT formazan was determined by measuring the absorbance at 570 nm (test wavelength) and 655 nm (reference wavelength) with a microplate reader. The concentration of L-Glu was estimated from a standard curve, which was constructed in each assay using cell-free medium containing known concentrations of L-Glu. L-Glu clearance was shown as the amount of L-Glu taken up by astrocytes, which was calculated from the concentration difference in the medium.

Treatment with Test Compounds. L-Glu was dissolved at 1 mM in phosphate-buffered saline and diluted to 100 μM with the culture medium. Compounds **1**, **2**, **3**, and **4** were dissolved at 100, 100, 100, and 10 mM, respectively, in dimethyl sulfoxide (DMSO) and diluted to the required final concentrations with the culture medium. The concentration of DMSO in the medium was controlled to be below 0.1%, because we had already confirmed that 0.1% DMSO has no effect on L-Glu transport activity or cell viability (data not shown). Cells were incubated with test compounds for 24 h. TBOA (IC50 = 48 μM for GLAST, 7 μM for GLT1) was freshly dissolved at 1 mM in culture medium for each experiment. ICI182,780 (IC50 = 0.29 nM for ERs), U0126 (IC50 = 72 nM for MEK1, 58 nM for MEK2), and LY294002 (IC50 = 1 μM for class 1 PI3K, 19 μM for class 2 PI3K) were dissolved at 1, 5, and 5 mM, respectively, in DMSO, and the solutions were diluted with culture medium to yield the required final concentrations. These inhibitors were coapplied with 1 nM test compounds (**1**−**4**) for 24 h.

Assay Procedure for Hormonal Effects on HEK293/hERα and HEK293/hERβ Reporter Cells. Human embryo kidney 293 cells (HEK293) were grown in FBS (+) DMEM in 100 mm dishes. Cells were subcultured once or twice a week at about 80% confluence. A solution of 12.4 μL of 2 M calcium ion, 100 ng/well reporter or negative control vector (pERE-TA-SEAP or pTA-SEAP, Clontech), 50 ng/well expression vector (pcDNA3 ERα or pcDNA3 ERβ, generous gift from Dr. Shige-aki Kato, University of Tokyo, Japan), and 100 ng/well positive control vector (pSV-β-galactosidase, Promega) was diluted to a final volume of 10 μL/well. This mixture was carefully added dropwise to the same volume of HEPES solution with slow vortexing, and the mixture was incubated at rt for 20 min to obtain a precipitate. Cells from the exponential growth phase were seeded (3.0×10^4 cells/ml) into 96-well plates the day before transfection. The cells were incubated with fresh medium for 1 h, then 1/10 volume of precipitate was added to each well and incubation was continued for 24 h at 37 °C in an atmosphere of 5% CO_2 in air. The medium was replaced with fresh FBS (-) medium and incubation was continued for a further 24 h. Then the cells were incubated with test compounds for 24 h at 37 °C in an atmosphere of 5% CO_2 in air. SEAP activity (Great EscapeTM SEAP chemiluminescence kit 2.0, Clontech) and β-galactosidase activity (β-Galactosidase Enzyme Assay System with Reporter Lysis Buffer, Promega) were measured with a Spectramax M5 microplate reader (Molecular Devices Japan, Tokyo, Japan). All transfections were performed in triplicate.

Statistical Analysis. Data were obtained from four independent experiments (averaged values of six wells for each) unless otherwise noted. Data are expressed as means ± SEM of these data. Tests of homogeneity of variance, normality, and distribution were performed to ensure that the assumptions required for standard parametric ANOVA were satisfied. Statistical analysis was performed by one-way repeated-measures ANOVA with post hoc Tukey's test for multiple pairwise comparisons.

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Author Contributions

†These two authors equally contributed to this Article. Individual author contributions: K.S. designed the biological experimental plan, performed biological experiments, data analysis, manuscript writing and preparation. J.K. and Y.S. performed experimental work. K.T. contributed to the data analysis. J.O., K.N. and Y.S. provided advice on the experimental direction. Y.O. carried out organic synthesis, data analysis and wrote portions of the manuscript. Y.S. carried out organic synthesis. T.O. designed and oversaw all organic chemistry studies, carried out organic synthesis and also performed data analysis and manuscript writing and preparation.

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Notes

The authors declare no competing financial interest.

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■ ABBREVIATIONS

βNAD; β-nicotinamide adenine dinucleotide; CNS; central nervous system; DMEM; Dulbecco's modified Eagle's medium; DMSO; dimethyl sulfoxide; E2; 17β-estradiol; ESI; electron spray ionization; FBS; fetal bovine serum; GLD; glutamate dehydrogenase; HEK-293; Human embryo kidney 293 cells; HRMS; high-resolution mass spectrometry; L-Glu; L-glutamate; MAPK; mitogen-activated protein kinase; MEK; mitogen-activated protein kinase/extracellular signal-regulated kinase; mERα; membrane-associated estrogen receptor α; mGluR5; metabotropic glutamate receptor 5; MPMS; 1-methoxy-5-methylphenazinium methyl sulfate; MTT; 3-(4,5-dimethyl-2-thiazolyl)-2,5-diphenyl-2H-tetrazolium bromide; nERs; nuclear estrogen receptors; PI3K; phosphatidylinositol 3-kinase; Tam; tamoxifen; TBOA; DL-threo-β-benzyloxyaspartic acid; TLC; thin-layer chromatography; TOF; time-of-flight

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