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ARTICLE

Disruption of lipid-raft localized $G\alpha_s$/tubulin complexes by antidepressants: a unique feature of HDAC6 inhibitors, SSRI and tricyclic compounds

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Current antidepressant therapies meet with variable therapeutic success and there is increasing interest in therapeutic approaches not based on monoamine signaling. Histone deacetylase 6 (HDAC6), which also deacetylates α-tubulin shows altered expression in mood disorders and HDAC6 knockout mice mimic traditional antidepressant treatments. Nonetheless, a mechanistic understanding for HDAC6 inhibitors in the treatment of depression remains elusive. Previously, we have shown that sustained treatment of rats or glioma cells with several antidepressants translocates $G\alpha_s$ from lipid rafts toward increased association with adenylyl cyclase (AC). Concomitant with this is a sustained increase in cAMP production. While $G\alpha_s$ modifies microtubule dynamics, tubulin also acts as an anchor for $G\alpha_s$ in lipid-rafts. Since HDAC-6 inhibitors potentiate α-tubulin acetylation, we hypothesize that acetylation of α-tubulin disrupts tubulin-$G\alpha_s$ raft-anchoring, rendering $G\alpha_s$ free to activate AC. To test this, C6 Glioma (C6) cells were treated with the HDAC-6 inhibitor, tubastatin-A. Chronic treatment with tubastatin-A not only increased α-tubulin acetylation but also translocated $G\alpha_s$ from lipid-rafts, without changing total $G\alpha_s$. Reciprocally, depletion of α-tubulin acetyl-transferase-1 ablated this phenomenon. While escitalopram and imipramine also disrupt $G\alpha_s$/tubulin complexes and translocate $G\alpha_s$ from rafts, they evoke no change in tubulin acetylation. Finally, two indicators of downstream cAMP signaling, cAMP response element binding protein phosphorylation (pCREB) and expression of brain-derived-neurotrophic-factor (BDNF) were both elevated by tubastatin-A. These findings suggest HDAC6 inhibitors show a cellular profile resembling traditional antidepressants, but have a distinct mode of action. They also reinforce the validity of antidepressant-induced $G\alpha_s$ translocation from lipid-rafts as a biosignature for antidepressant response that may be useful in the development of new antidepressant compounds.

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INTRODUCTION

Major depressive disorder (MDD) is a debilitating mental illness affecting one in six people sometime during their lifetime. Various therapies are available but as many as 30% of patients fail to achieve remission. This reinforces the need for novel therapeutics. There is evidence that histone deacetylase enzymes (HDACs) play a role in pathophysiology and treatment of MDD and other neuropsychiatric disorders [1–3]. Out of the 11 different members of HDAC enzymes, HDACs 2, 4, 5, 6, and 8 mRNAs levels were found to be altered in blood cells and postmortem brains of patients with mood disorders [1, 4]. Similarly, several HDAC inhibitors promote behavioral responses in rodent models similar to those seen with antidepressants [1, 5]. Unlike all other HDACs involved in deacetylation of histone proteins, HDAC6 is unique, as it is localized exclusively in the cytoplasm and is involved in deacetylation of cytosolic proteins such as, tubulin, cortactin, and Hsp90 [6, 7]. Furthermore, human studies using peripheral white blood cells from MDD patients showed altered mRNA levels of HDAC6 [4]. Dorsal and median raphe nuclei show high expression of HDAC6, consistent with possible HDAC6 roles in regulation of emotional behaviors. HDAC6-deficient mice exhibit hyperactivity, decreased anxiety, and behavior similar to those seen after administration of antidepressants [8–10] and are also resilient to stress paradigms [11]. However, the mechanisms of action of HDAC6 enzyme inhibition in conferring resilience are still not known.

Brain tissue from animal models of depression and chronic stress show alterations in cytoskeletal microtubules [12–14] resulting in neuronal plasticity failure in limbic/cortical areas plus neuronal atrophy and decreased neurogenesis in hippocampus [15]. Microtubules are involved in regulating cell morphology, intracellular transport, and dynamic movement of associated proteins and undergo constant cycles of polymerization and depolymerization via hydrolysis of bound GTP to GDP by intrinsic GTPase activity [16]. HDAC6 associates with microtubules (α and β tubulin heterodimers) [6] and deacetylates α-tubulin [17, 18], increasing dynamic instability of microtubules [19]. Additionally, HDAC6 inhibition has been shown to ameliorate CNS injury characterized by oxidative stress-induced neurodegeneration and insufficient axonal regeneration [20]. Increased acetylation of α-tubulin was found to be critical for the regulation of migration, projection length, and branching of developing cortical neurons [21] and the expression of a non-acetylable α-tubulin mutant in

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cortical neurons leads to decreases in axonal length and impaired branching of projection neurons.

[^{11}C] (*R*)-rolipram positron-emission tomography (PET) imaging suggests a global decrease of cAMP in brains from depressed subjects [22] and blood cells from depressed patients showed decreased $G\alpha_s$-stimulated AC compared to controls [23, 24]. Successful antidepressant treatment restores cAMP in both platelets and brain tissue [24, 25]. The $G\alpha_s$ subunit has been shown to localize in cholesterol and sphingolipid enriched membrane microdomains called lipid rafts and raft localization attenuates $G\alpha_s$ activity [26–36]. Postmortem human brain tissue from depressed subjects showed increased $G\alpha_s$ in lipid rafts [37]. The raft-ensconced Gαs is less likely to activate AC [28, 30] due to decreased Gαs/AC functional coupling.

Antidepressants activate $G\alpha_s$ by translocating it from lipid rafts, to AC in the non-raft membrane domain, thus increasing cAMP [29, 38]. Antidepressant treatment also increases the physical association between $G\alpha_s$ and AC in rat cerebral cortex after 3-weeks, but not 1- week antidepressant treatment [39]. Antidepressants have also been shown to accumulate in lipid-raft domains [40]. Taken together, these observations reflect some involvement of Gαs lipid rafts, adenylyl cyclase and tubulin in the pathophysiology and treatment of MDD. We suggest that tubulin anchors $G\alpha_s$ within lipid rafts preventing it from activating AC and that antidepressants mitigate the association between tubulin and $G\alpha_s$ in those rafts, increasing the activation of AC.

This study suggests a novel mechanism of action for HDAC6 inhibition as an antidepressant. We report here that HDAC6 inhibitor-induced α-tubulin acetylation facilitates trafficking of $G\alpha_s$ out of rafts to activate downstream cAMP signaling and diminishes the association between $G\alpha_s$ and tubulin in lipid rafts. This represents a unique antidepressant pathway as other antidepressants have no effect on tubulin acetylation even as they also diminish the association between $G\alpha_s$ and tubulin. Furthermore, these data illustrate how lipid-raft microdomains provide a signaling platform for interactions between $G\alpha_s$ and tubulin to regulate cAMP mediated gene expression and possible antidepressant effects. We also reinforce the utility of translocation of $G\alpha_s$ from lipid-rafts as a hallmark of antidepressant action.

MATERIALS AND METHODS

Cell culture and drug treatments

C6 cells in 150 cm flasks were cultured in Dulbecco's modified Eagle's medium, 4.5 g glucose/l, 10% newborn calf serum (Hyclone Laboratories, Logan, UT, USA), 100 mg/ml penicillin and streptomycin (only for lipid-raft isolation and immunoprecipitation and cells in all other experiments were grown without antibiotics) at 37 °C in humidified 5% CO_2 atmosphere. The cells were treated with 10 μM of escitalopram (gift from Lundbeck, Copenhagen, Denmark), 10 μM Tubastatin-A (Sigma-Aldrich, St. Louis, MO), 10 μM imipramine (Tocris), 500 nM Aripiprazole (Tocris), 10 μM SAHA (Sigma-Aldrich), 10 μM TSA (Sigma-Aldrich), or ACY-738 (Acetylon Pharmaceuticals) for the indicated durations. The culture media and drug were changed daily. There was no change in morphology of cells during the period of exposure to the drugs.

Isolation of lipid raft/Caveolae

Following drug exposure, C6 cells were placed immediately on ice and scraped in detergent-free tricine buffer (250 Mm sucrose, 1 mM EDTA, 20 mM tricine, pH 7.4). The cellular material was homogenized and centrifuged at low speed (1400×*g* for 5 min at 4 °C) to precipitate nuclear material. The resulting supernatant (Homogenate-H) was collected, mixed with 30% Percoll in tricine buffer and subjected to ultracentrifugation for 25 min (Beckmann MLS50 rotor, 77,000×*g*, at 4 °C) to collect plasma membrane fraction (PM). PMs were collected and sonicated (3 × 3-s bursts). The sonicated material was mixed with 60% sucrose (to a final concentration of 40%), overlaid with a 35-5% step sucrose gradient and subjected to overnight ultracentrifugation (Beckman MLS50 rotor, 87,400×*g* at 4 °C). Fractions were collected every 400 μL from the top sucrose layer and proteins were precipitated using 0.25 volume TCA-deoxycholic acid [100% (wt/vol)] TCA in double distilled water. Precipitates were made soluble in 0.1% (wt. vol) deoxycholic acid.

Immunoprecipitation

A mAb against $G\alpha_s$ (NeuroMab clone N192/12, Davis, CA, USA, catalog #75-211) and α-tubulin (SIGMA) conjugated to sheep anti-mouse-coated paramagnetic Dynabeads (Invitrogen, Grand Island, NY) according to manufacturer's protocol. Lysates were isolated from tubastatin-A treated and untreated C6 cells, Equal amounts of protein (500 μg) from each sample was adjusted to a final volume of 1.2 ml with PBS containing 60 mM octyl-β-D-glucopyranoside (Sigma-Aldrich #29836-26-8) and incubated with the antibody-bead conjugates overnight at 4 °C. The $G\alpha_s$ and α-tubulin immunoprecipitates were collected and washed three times with cold PBS. Samples incubated with beads lacking any antibody served to control for non-specific protein binding.

SDS-page and western blotting

Samples were assayed for protein via a Nanodrop 2000c spectrophotometer and equal quantities were loaded onto Stain-Free acrylamide gel for SDS-PAGE (Bio-Rad, Hercules, CA, USA). Gels were transferred to Nitrocellulose membranes (Bio-Rad, Hercules, CA USA) for western blotting. The membranes were blocked with 5% non-fat dry milk diluted in TBS-T (10 mM Tris-HCl, 159 mM NaCl, and 0.1% Tween 20, pH 7.4) for 1 h. Following the blocking step, membranes were washed with Tris-buffered saline/Tween 20 and then incubated with an anti-$G\alpha_s$ monoclonal antibody (NeuroMab clone N192/12, Davis, CA, USA, catalog #75-211), anti-$G\alpha_s$ polyclonal antibody (EMD Millipore, Billerica, MA, USA, catalog #06-237), acetyl-α-tubulin (Lysine-40) (Sigma Clone 6-11B-1), α-tubulin (Sigma), caveolin-1 (BD Biosci #610059), β-actin (Sigma Clone AC-74), p-CREB (Cell Signaling #9198), CREB (Cell Signaling #9197), BDNF (Cell Signaling #3987), anti-ATAT-1 (Neuromab), Acetyl-Histone-3 (Cell Signaling #9649), or Histone-3 (Cell Signaling #4496) overnight at 4 °C. Membranes were washed with TBS-T and incubated with a secondary antibody [HRP-linked anti-mouse antibody IgG F(ab')2 or HRP-linked anti-rabbit antibody IgG F(ab')2] (Jackson ImmunoResearch, West Grove, PA, USA, catalog #115-036-072 for mouse, and catalog #111-036-047 for rabbit, RRID) for 1 h at room temperature, washed, and developed using ECL Luminata Forte chemiluminescent reagent (Millipore, Billerica, MA, USA). Blots were imaged using a Chemidoc computerized densitometer (Bio-Rad, Hercules, CA, USA) and quantified by ImageLab 3.0 software (Bio-Rad, Hercules, CA, USA). In all experiments, the original gels were visualized using BioRad stainfree technology to verify protein loading.

Depletion of alpha tubulin acetyl transferase-1 (ATAT-1)

Expression of ATAT-1 was inhibited with a SMARTpool: ON-TARGET plus ATAT-1siRNA (Catalog #L-014510-02-0005) and scrambled control siRNA (Dharmacon, Inc, Pittsburg, PA). Briefly, C6 cells at 80% confluence were transfected with 50 nM siRNA using DharmaFECT-1. Cells were used 24 h after transfection when expression levels of ATAT-1 were reduced by >90% as determined by immunoblot analysis using ATAT-1 antibody (Sigma-Aldrich #A106171).

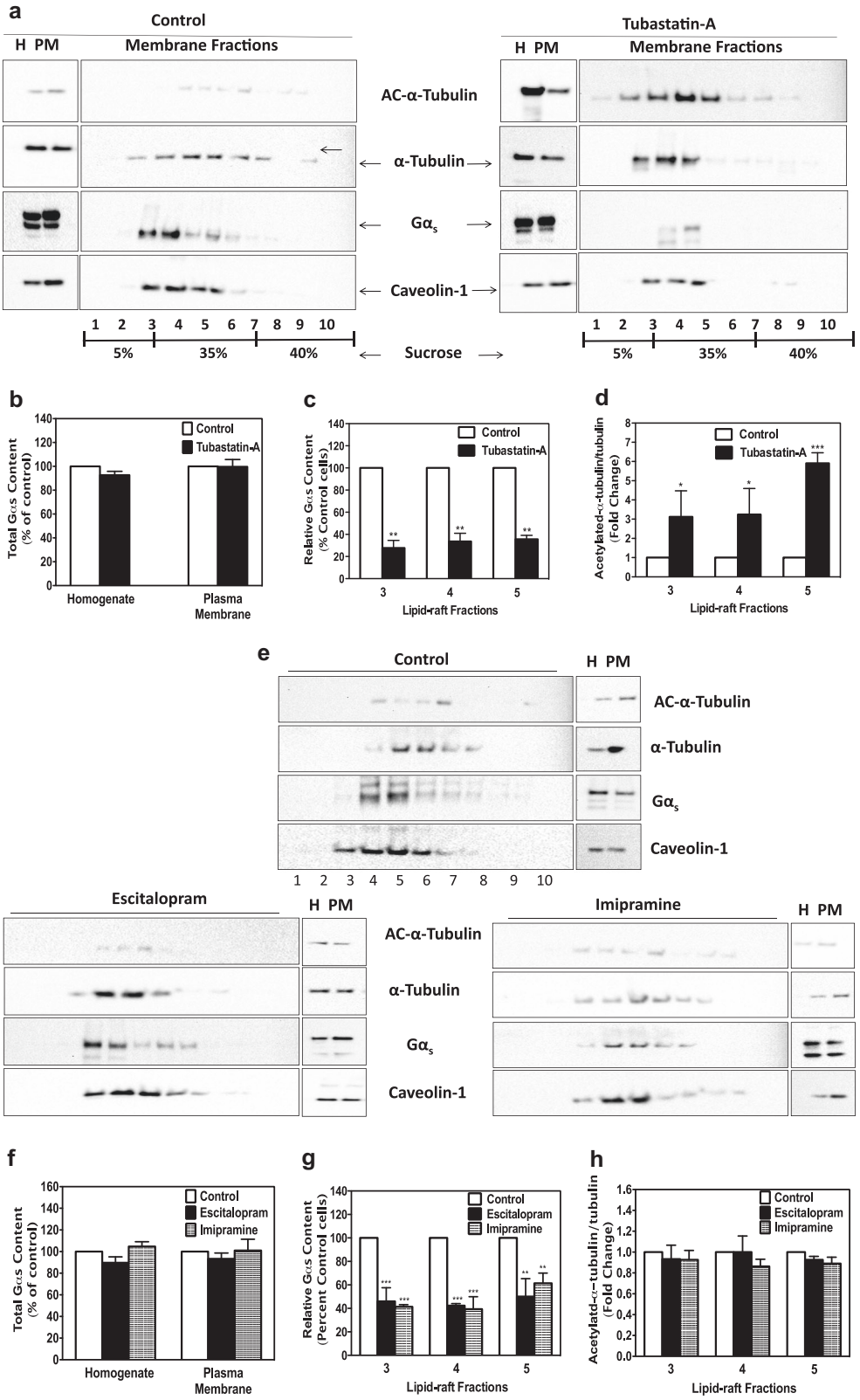
Transfection and generation of stable cell lines

C6 glioma were cultured until 80% confluent and then trypsinized into suspension for electroporation with the Invitrogen Neon Transfection System following the manufacturer's protocols. Approximately 5 μg of DNA was used per one million cells. After transfection, cells were plated in an appropriate name the dish

dish for 24 h before further lysis, imaging, or clonal selection. To isolate a stable expressing cell line, cells were treated with 1 mg/ml of G418 for at least three passages (~1 week each) and individual clones were selected using fluorescence-activated cell sorting. After sorting, G418 was not needed to maintain stable expression.

Fluorescence recovery after photobleaching (FRAP)

C6 glioma cells stably transfected with GFP- $G\alpha_s$ were plated on glass microscopy dishes and treated with escitalopram (10 μM), or tubastatin-A (10 μM) for 3 days. On the day of imaging, drug was washed out 1 h prior to imaging and media was replaced with low serum (2.5% NCS) phenol red-free DMEM to reduce background



fluorescence. Temperature was maintained at 37 °C using a heated stage assembly during imaging on a Zeiss LSM 710 META at 512 × 512 resolution using an open pinhole to maximize signal but minimize photobleaching. Total of 150 data points ~300 ms apart, including 10 pre-bleach values, were measured for each cell. Zeiss Zen software was used to calculate FRAP recovery half-time utilizing a one-phase association fit, correcting for total photobleaching of the analyzed regions, similar to that described previously [41].

Viral infection and cAMP quantification

C6 cells were grown on glass bottom microscope dishes, pretreated with/without tubastatin-A (3 days) were infected with (1.09×10^9 VG/mL) cADDIS BacMam virus encoding the green "up" cAMP sensor (Montana Molecular, Bozeman, MT, USA) and grown for 24–26 h before live imaging under a ×40 objective on a Zeiss 880. Cells were serum starved with 1% serum for 2–3 h before Isoproterenol (1 μM) treatment. Images were taken every 30 s. Average responses from 4 to 10 cells were selected from the visual field and fluorescence was normalized to baseline fluorescence for each experiment.

Statistical analysis

Western blot bands were quantified to arbitrary units (AU) using Image-J software. The AU values derived from control were set to one (or 100%) compared to treatment AU values. The normalized results are illustrated in bar graphs. While there is an apparent lack of variance for the controls in these figures, the measured band intensity (AU) for each control set was distinct. Unpaired *t*-test for AU from control vs. treatment conditions were performed followed by Welch's correction. For simplification purposes, the graphs are represented with either fold change or percent change with *p*-values derived from statistical analysis. Thus, the controls do not show variance in illustrations. Detailed statistical analysis is described in legend for each figure. Data are represented from at least three replicate experiments. Significant differences ($p < 0.05$) were determined by unpaired *t*-test or ANOVA as specified in figure legends using the Prism version 3.0 software package for statistical analysis (GraphPad Software Inc., San Diego, CA).

RESULTS

HDAC6 inhibition increases α-tubulin acetylation and translocates $G\alpha_s$ from lipid rafts in a manner similar to that seen for other monoamine-centric antidepressants

C6 cells were first treated with increasing doses of tubastatin-A for 4 h, showing peaks in α-tubulin acetylation (Lysine-40) at 10 μM (Supplementary figure S1). Higher concentrations were cytotoxic. Therefore, 10 μM doses of tubastatin-A were used for all experiments. Tubastatin-A treatment was specific to α-tubulin acetylation (HDAC6 enzyme inhibition) as no changes in Histone (H3) acetylation/total H3 were detected at any of the drug concentrations used (Supplementary figure S1), suggesting that effects of HDAC6 inhibition occurs independent of transcription. Additionally, pretreatment of cells with pan-HDAC inhibitors, such as SAHA and TSA showed acetylation of both nuclear histone proteins (H3) and microtubules (α-tubulin); whereas, tubastatin-A and more potent HDAC6 inhibitor with increased brain availability, ACY-738, showed increased acetylation only at microtubule element, α-tubulin (Supplementary Figure S4). This suggests the microtubule specificity of HDAC6 inhibition-induced molecular changes.

Post-nuclear material (Homogenate-H), plasma membrane (PM), and lipid-raft membranes (3–5 fractions) were isolated using sucrose-density gradient centrifugation. Brief tubastatin-A treatment (4 h, 1 day) did not translocate $G\alpha_s$ from lipid-rafts. However, 2 day treatment resulted in initiation of translocation, reaching maximum effect at 3 day post-treatment (Supplementary data S2), without altering total $G\alpha_s$ in either post-nuclear homogenate (H) or plasma membrane (PM). Three day tubastatin-A treatment increases acetylation of α-tubulin 5–6-fold in lipid-raft membrane fractions (Caveolin-1 enriched fractions 3–5) (Fig. 1a and Supplementary Figure S2) compared to controls; whereas, the levels of total $G\alpha_s$ or total-α-tubulin in treatment vs. control post-nuclear homogenate (H) and plasma membrane (PM), remained unaltered (Fig. 1b). Similar to our past findings using SSRIs and tricyclic antidepressants [29, 38, 43], tubastatin-A treatment showed a 60–70% decrease in localization of Gαs subunits to lipid-raft fractions (Fig. 1 a, c). As a contrapositive, we wished to determine whether depletion of tubulin-acetyl-transferase can result in increased localization of $G\alpha_s$ in lipid-rafts. C6 cells were depleted of the enzyme responsible for acetylation of α-tubulin at Lysine-40, α-tubulin acetyl transferase 1 (ATAT-1), resulting in increased localization of $G\alpha_s$ in lipid-rafts as a consequence of markedly decreased tubulin acetylation (Supplementary Figure S3). As expected, treatment of ATAT-1 depleted C6 cells with tubastatin-A (3 days), showed no effect on the translocation status of $G\alpha_s$ from lipid-rafts (Supplementary Figure S3).

Antidepressant-induced translocation of $G\alpha_s$ from lipid rafts is independent of α-tubulin acetylation

Previous studies have shown that sustained treatment (3 weeks in rats; 3 days in cells) with monoamine-centric antidepressants translocated $G\alpha_s$ subunits out of lipid-raft domains [29, 38, 43]. Similarly, tubastatin-A treatment-induced $G\alpha_s$ translocation from lipid rafts and this coincided with a greater degree of acetylation of α-tubulin (Fig. 1a, b, c, d). In order to determine whether tubulin acetylation accompanied treatment with SSRIs or tricyclic antidepressants, C6 cells were treated with escitalopram (10 μM), or Imipramine (10 μM) or vehicle control for 3 days followed by detection of tubulin acetylation. Similar to previous observations, escitalopram, and imipramine treatment showed translocation of $G\alpha_s$ subunit out of lipid rafts (Fig. 1e, g) without changes in total $G\alpha_s$ (Fig. 1f). However, there was no change in acetylation of α-tubulin compared to controls (Fig. 1h). Therefore, while SSRI, tricyclic and tubastatin-A treatments all result in depletion of raft localized $G\alpha_s$ subunit only the latter promotes α-tubulin acetylation.

Fig. 1 Sustained treatment with tubastatin-A, escitalopram, or imipramine induce translocation of $G\alpha_s$ out of lipid-raft domains, but only tubastatin-A increases acetylation of α-tubulin. C6 glioma cells were treated (3 days) with either tubastatin-A (10 μM), escitalopram (10 μM), imipramine (10 μM), or vehicle control and cells were collected for isolation of lipid-raft domains using sucrose density gradient centrifugation. Ten different fractions were collected (A&E). Lipid-raft domains (fractions 3–5) were revealed via enrichment of Caveolin-1, a lipid-raft protein. The collected membrane fractions (1–10), cell homogenate (H) and isolated plasma membrane (PM) were prepared for SDS-PAGE and membranes were incubated with Cav1, acetylated-α-tubulin, total α-tubulin and $G\alpha_s$ antibodies. Three replicate experiments were conducted and $G\alpha_s$, acetylated-α-tubulin and total tubulin from Homogenate (H), Plasma Membrane (PM), and lipid-rafts were quantified and plotted as percent of $G\alpha_s$ and fold change in acetylation compared to control samples **b**, **c**, **d**, **f**, **g**, **h**. Data in **b**, **c**, **d** were analyzed using unpaired *t*-test followed by Welch's correction and mean ± SEM are represented as fold change or percent change compared to controls. Each condition was compared to vehicle control by unpaired *t*-test. The *p*-values obtained from this test were used for the represented graphs in each figure. Data in figure **f**, **g**, **h** were analyzed by one way ANOVA for comparisons between Control, Escitalopram, and Imipramine followed by Kruskal–Wallis test (*$p < 0.05$ compared to vehicle control; **$p < 0.01$ compared to vehicle control, ***$p < 0.001$ compared to vehicle control)

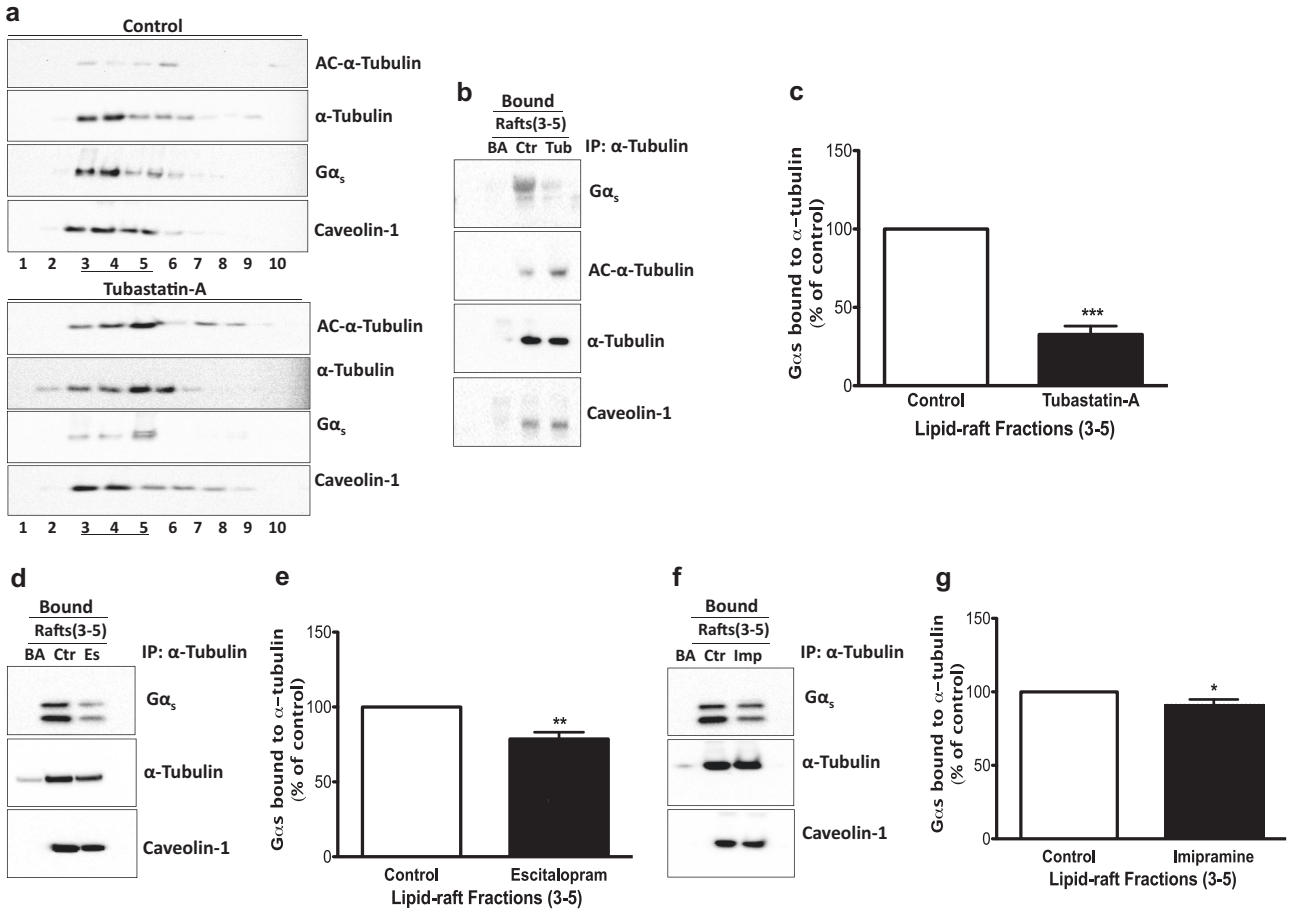


Fig. 2 Tubastatin-A and antidepressant treatment disrupts $G\alpha_s$/α-tubulin complexes in lipid-raft domains. C6 glioma cells treated (3 days) with tubastatin-A (Tub)(10 μM), escitalopram (Es) (10 μM), imipramine (Imp) (10 μM), or vehicle control (Ctr) were processed by sucrose density gradient centrifugation to isolate lipid-raft domains **a**. Raft domain (fractions 3–5) samples were used as input for immunoprecipitation (IP) using Dynabeads conjugated with α-tubulin antibody. The bound immunoprecipitate (Bound) was western blotted and nitrocellulose membranes were probed with acetylated-α-tubulin, α-tubulin, $G\alpha_s$, and Caveolin-1 antibodies **b**, **d**, **f**. BA (Beads alone) denotes unconjugated Dynabeads to account for non-specific binding. Samples are representative of three individual experiments **a**, **b**, **d**, **f**. The amount of $G\alpha_s$ bound to α-tubulin is quantified from these three individual experiments and expressed as percent change in amount of $G\alpha_s$ between control and tubastatin-A treated samples **c**, **e**, **g**. Each condition was compared to vehicle control. Data were analyzed using unpaired *t*-test followed by Welch's correction and mean ± SEM are represented as fold change compared to controls. The *p*-values obtained from this test were used for the represented graphs in each figure. (*$p < 0.05$ compared to vehicle control; **$p < 0.01$ compared to vehicle control; ***$p < 0.001$ compared to vehicle control)

The stability of $G\alpha_s$/α-tubulin complex in lipid rafts is dependent on acetylation of α-tubulin

Based on previous studies, the membrane lipid-raft domains are not only enriched in G-protein subunit, $G\alpha_s$, but are also centers for microtubule organization [44]. Lipid rafts, therefore, act as platforms docking tubulin/$G\alpha_s$ complexes, which dampen AC activation [30]. HDAC6 inhibition increases α-tubulin acetylation and $G\alpha_s$ movement out of lipid-rafts, consistent with increased binding of tubulin dimers to one another (microtubule stability) at the expense of $G\alpha_s$/tubulin complex formation. To test this, we probed for $G\alpha_s$/tubulin complex formation using co-immunoprecipitation. We are aware that acetylation is on α-tubulin and the binding site for $G\alpha_s$ is on β-tubulin [45, 46], but acetylation has significant effects on the tubulin dimer [47]. Given that the Gαs/tubulin complexes are concentrated in lipid-rafts, we focused on $G\alpha_s$/tubulin therein. Lipid rafts were isolated from C6 cells treated with either tubastatin-A or vehicle control and used as starting material (fractions 3–5 enriched in Cav1) for incubation with antibody conjugated Dynabeads (Fig. 2a). Immunoprecipitates (Bound fraction) from chronic tubastatin-A treated lipid rafts contained fewer $G\alpha_s$/tubulin complexes than control (Fig. 2b, c). Similarly, treatment with escitalopram and imipramine, also disrupted lipid raft $G\alpha_s$/tubulin complexes, without any measurable acetylation level changes in lipid-raft localized α-tubulin (Fig. 2d, e, f, g). Therefore, several antidepressant treatments decrease $G\alpha_s$/tubulin interaction, but only HDAC6 inhibitors do this by increasing tubulin acetylation.

HDAC6 inhibition decreases lateral diffusion of $G\alpha_s$ in the plasma membrane

$G\alpha_s$ translocates from membrane lipid-rafts and increasingly couples with AC subsequent to antidepressant treatment [41]. To determine whether tubastatin-A produces similar effects, $G\alpha_s$ membrane mobility was assayed using fluorescence recovery after photobleaching (FRAP) [41] in C6 cells stably expressing GFP-$G\alpha_s$. Consistent with antidepressant treatment of these cells, tubastatin-A treatments showed longer recovery time of GFP-$G\alpha_s$ fluorescence compared to no-treatment control or to non-antidepressant neuroactive compounds [41] (Fig. 3a, b, c). The longer recovery time is due to decreased mobility of $G\alpha_s$, which appears due to increased $G\alpha_s$ association with AC and the relative immobility of the resultant large molecular complex. Representative membrane photobleaching and recovery are demonstrated in Fig. 3a. Relative to controls, cells treated with tubastatin-A

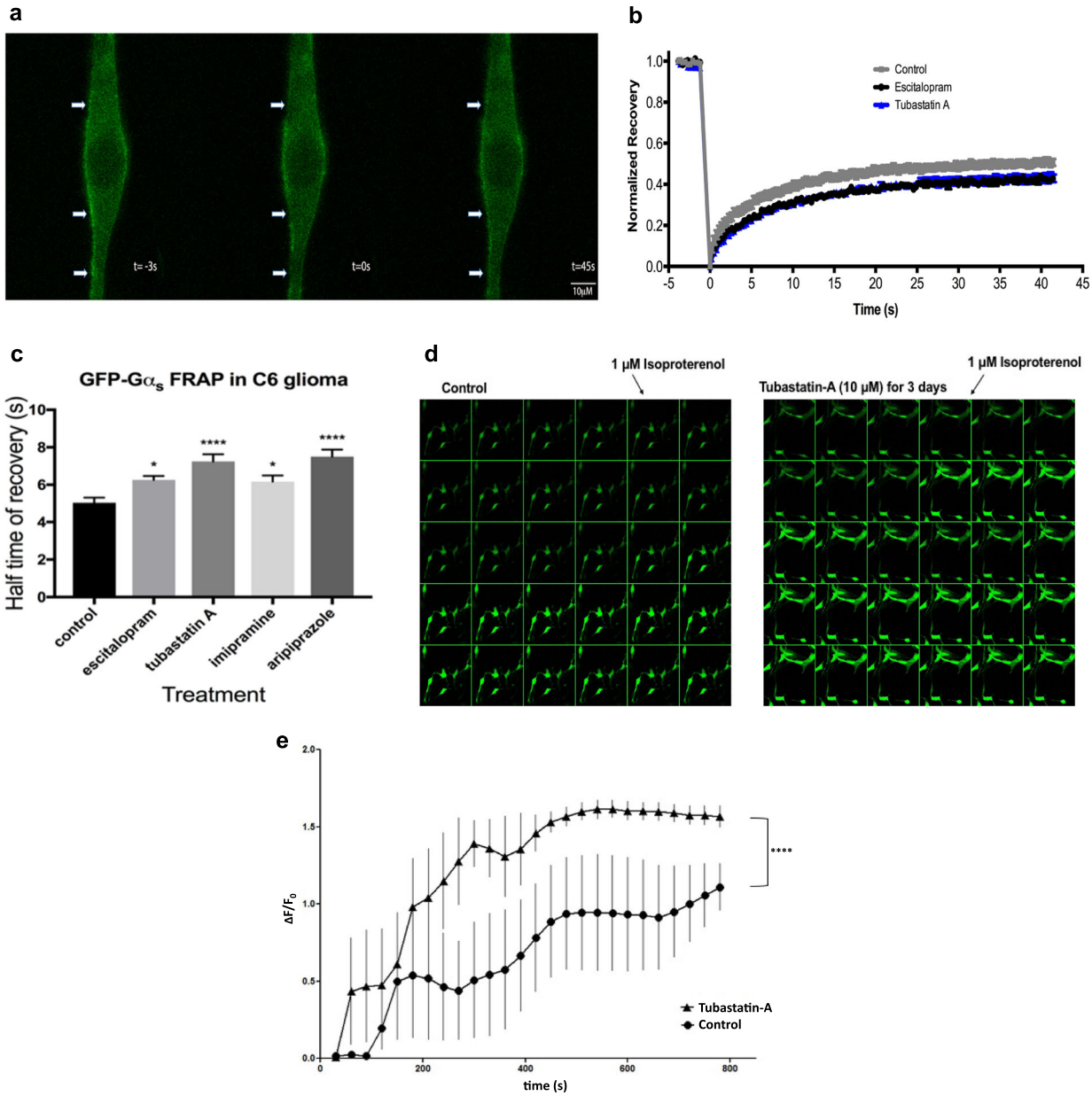


Fig. 3 Tubastatin-A slows the lateral mobility of membrane localized GFP-Gα_s after photobleaching and enhances isoproterenol elicited cAMP accumulation. C6 cells stably expressing GFP-Gα_s **a** were treated with the indicated compound and subjected to FRAP analysis as described in the Methods section. Half-time of recovery for GFP-Gα_s is increased after treatment (3 days) with tubastatin-A (10 μM), escitalopram (10 μM), imipramine (10 μM), and aripiprazole (500 nM) **b**, **c**, and various other antidepressant drugs of different chemical and functional classes [41]. Sample size represents the number of cells assayed, with a minimum of 48 and a maximum of 84 cells assayed per experiment. Data were analyzed by Kruskal–Wallis test ($F = 8.767$) followed by Dunn's multiple comparison test. Data are represented as mean ± SEM. (*$p < 0.05$ compared to vehicle control; **$p < 0.01$ compared to vehicle control; ****$p < .0001$ compared to vehicle control). In order to measure cAMP accumulation, C6 cells were grown on glass bottom microscope dishes, pretreated with/without tubastatin-A (3 days) were infected with (1.09 × 109 VG/mL) cADDIS BacMam virus encoding the green "up" cAMP sensor and grown for 24–26 h before live imaging under a ×40 objective on a Zeiss 880. Cells were serum starved with 1% serum for 2–3 h before Isoproterenol (1 μM) treatment. Images were taken every 30 s. Average responses from 4 to 10 cells were selected from the visual field and fluorescence was normalized to baseline fluorescence for each experiment. The montage shown here **d** is representative of four replicate experiments and the fluorescence values, **e**, from each experiment were quantified, corrected for baseline fluorescence (ΔF/F0), and the data are represented as mean ± SE ****$p < 0.0001$ **e**

demonstrated a significant increase in half-time to maximal recovery, similar to changes in recovery half-time observed with antidepressants imipramine and escitalopram. The slowed recovery of fluorescence, represented as an increase in FRAP recovery half-time, reflects the decreased mobility of Gα_s, increasingly coupled to the large, multi-transmembrane AC protein. This "antidepressant signature" of slowed lateral membrane mobility is detected after treatment with a variety of antidepressant drugs of different functional and chemical classes, but not psychiatric drugs lacking antidepressant activity including antipsychotics and anxiolytics [41]. We additionally present the example of aripiprazole, an atypical antipsychotic which has some antidepressant activity [42]. As occurs with all antidepressants tested, treatment of C6 cells with aripiprazole or tubastatin-A retards GFP-Gα_s

fluorescence recovery, revealing a consistent antidepressant signature.

HDAC6 inhibition enhances cAMP production, downstream CREB activation and overexpression of BDNF similar to that of SSRI and tricyclic antidepressants

Detection of $G\alpha_s$ from lipid rafts and the resultant increase in $G\alpha_s$/AC complexes also results in a sustained increase in cAMP. Tubastatin-A treated cells showed high-basal levels of cAMP levels. However, when cells were stimulated by the $G\alpha_s$-coupled agonist isoproterenol (1 μM), tubastatin-A treated cells show both a quicker and more robust increase in fluorescence, indicating an enhanced coupling of $G\alpha_s$ and adenylyl cyclase (Fig. 3d, e). Sequelae of sustained cAMP elevation include increased pCREB and BDNF. Three day treatment of C6 cells with tubastatin-A-induced phosphorylation of CREB (p-CREB-Ser133) (threefold increase) (Fig. 4a, b, c). Correspondingly, a CREB-activated gene product important for antidepressant response, BDNF, was increased (~1.7-fold) compared to controls (Fig. 4d, e). As shown previously in glial cells [48], chronic treatments with escitalopram and imipramine showed similar increases in CREB activation (p-CREB) and BDNF (Fig. 4f, g, h, i, j, k, l, m).

DISCUSSION

The major findings of this study reveal a commonality between SSRIs, tricyclic antidepressants and HDAC6 inhibitors in translocation of $G\alpha_s$. This study also suggests that the disruption of complexes between $G\alpha_s$ and tubulin in lipid rafts is a concomitant of antidepressant response. While many current antidepressants inhibit monoamine uptake, C6 cells lack monoamine transporters [49], yet remain antidepressant-responsive increasing $G\alpha_s$-AC coupling and translocating $G\alpha_s$ from lipid rafts [43]. While neurons are generally assumed to be the targets of antidepressants, there is evidence for involvement of glia in both depression [50] and in the action of antidepressants [51, 52]. Furthermore, antidepressant treatment induces expression and release of glial cell derived neurotrophic factor (GDNF), promoting survival of neurons [53, 54]. The protein expression profile and downstream cAMP responses to drugs and pathological are similar in both primary astrocytes and C6G cells. Nonetheless, C6 glioma cells are not astrocytes and translation of these findings to glia must be tempered. The C6 cells stably transfected with $G\alpha_s$-GFP can be used for FRAP with relative ease.

A role for HDAC6 inhibitors in alleviating depression and anxiety-like behaviors has been suggested. HDAC6 KO mice show increased amounts of acetylated α-tubulin in different tissues, including brain [55]. HDAC6- depleted animals also showed significantly decreased immobility time in tail-suspension test, a behavior similar to that see after administration of antidepressants [11]. Recently, novel HDAC6 inhibitors with increased brain bioavailability showed antidepressant activity in the tail-suspension test and social defeat paradigm. The studies also showed that behaviorally inactive doses of HDAC6 inhibitor can potentiate SSRI effects in rodents [9]. However, the mechanistic link between increased α-tubulin acetylation and improved performance on behavioral testing was not established.

Studies in postmortem human brain tissue and animals have shown neuronal plasticity as a hallmark of antidepressant actions. These structural changes require cytoskeletal modifications, such as more dynamic forms of microtubules [56] and rapid polymerization/depolymerization events. These result in elongation and shortening of cell processes, essential for synaptogenesis [56–59]. Furthermore, proteomic studies from postmortem brain tissue of MDD subjects showed changes in proteins involved in cytoskeletal arrangement, neurotransmission and synaptic function [60].

Structural plasticity in brain during stress is correlated with defects in microtubules and SSRI treatment (Fluoxetine) counters this [14, 61]. In vivo studies in experimental models of stress and depression show α-tubulin isoform changes consistent with previous studies showing decreases in microtubule dynamics [61]. Acute Fluoxetine treatment increased α-tubulin acetylation, whereas chronic treatment resulted in decreased acetylation [62, 63] in rat hippocampal neurons. The melatonin-based antidepressant, agomelatin, has also been shown to induce microtubule alterations in rat hippocampal tissue [64]. In C6 cells, we see no changes in tubulin acetylation in response to 3-day treatment with fluoxetine. Whether this is due to cell type or is reflective of in vitro treatment remains to be determined.

Our previous work in C6 cells has shown that, lipid-rafts, cholesterol- and sphingolipid-rich specialized membrane microdomains, are enriched in G-protein subunit, $G\alpha_s$. Antidepressant treatment of these cells evokes $G\alpha_s$ translocation from lipid rafts, serving as a potential biosignature for antidepressant action [29, 43]. We have also shown that $G\alpha_s$ is internalized in lipid raft vesicles and that it becomes free in the cytosol [28]. It appears that Gαs is maintained in the activated state following internalization [65].

Activated $G\alpha_s$ binds tubulin resulting in increased microtubule dynamics and neurite outgrowth [66, 67] due to activation of tubulin GTPase [68]. Increased α-tubulin acetylation results in greater stability of microtubules [69, 70]. There is mounting evidence showing that both $G\alpha_s$ and tubulin are localized in lipid-raft domains [44, 71], therefore, it is suggested that tubulin acts as an anchor for $G\alpha_s$ within the rafts. Disruption of either lipid rafts or microtubules causes increased cAMP production [28, 44]. Herein, we show that the antidepressant treatment disrupts $G\alpha_s$/tubulin complexes in lipid rafts (Fig. 2d, e, f, g). HDAC6 inhibition (Tubastatin-A) has the same effect (Fig. 2a, b, c). Reciprocally, when ATAT-1 was knocked-down in C6 cells, tubulin acetylation decreased, resulting in more $G\alpha_s$ ensconced in lipid rafts (Supplementary Figure S3). These results support our hypothesis that tubulin anchors $G\alpha_s$ in rafts preventing it from activating AC. Note also that the apparent binding site for tubulin on $G\alpha_s$ [46, 68] is not consistent with simultaneous binding of tubulin and AC by $G\alpha_s$. Thus, it appears that $G\alpha_s$ is quiescent when associated with tubulin and activated when it breaks that complex and exits lipid rafts.

Postmortem brain tissue derived from depressed subjects showed increased localization of $G\alpha_s$ in lipid rafts and antidepressant treatments induce movement out of rafts [29]. Fluorescence recovery after photobleaching (FRAP) of GFP-$G\alpha_s$ is retarded after treatment with a large number of antidepressants, but not other hydrophobic neuroleptic drugs [41]. Based on this assay, we have been able to assign an antidepressant biosignature to several HDAC6 inhibitors (Fig. 3a, b, c) similar to that of monoamine-centric antidepressants.

AC activation, sustained cAMP increase and activated cAMP response element binding protein (CREB) is a well-established cellular pathway for antidepressant response. Rodent studies using traditional antidepressants (SSRIs) show increased AC activity [72], CREB activation [73–75]. These studies suggest that AC-induced cAMP generation, and pCREB are relevant to the treatment of depression and recent PET evidence suggests cAMP is damped in brains of subjects with MDD, returning to baseline after response to antidepressant therapy [25]. Consistent to the previous studies, the treatment with tubastatin-A showed an increase in cAMP generation (Fig. 3d, e) and corresponding downstream activation of CREB (phospho-CREB-133), without any change in levels of total CREB (Fig. 4b), similar to that of escitalopram and imipramine (Fig. 4f, h). Activated CREB is a transcription factor essential for upregulation of specific target genes, including brain derived neurotrophic factor (BDNF) [76, 77]

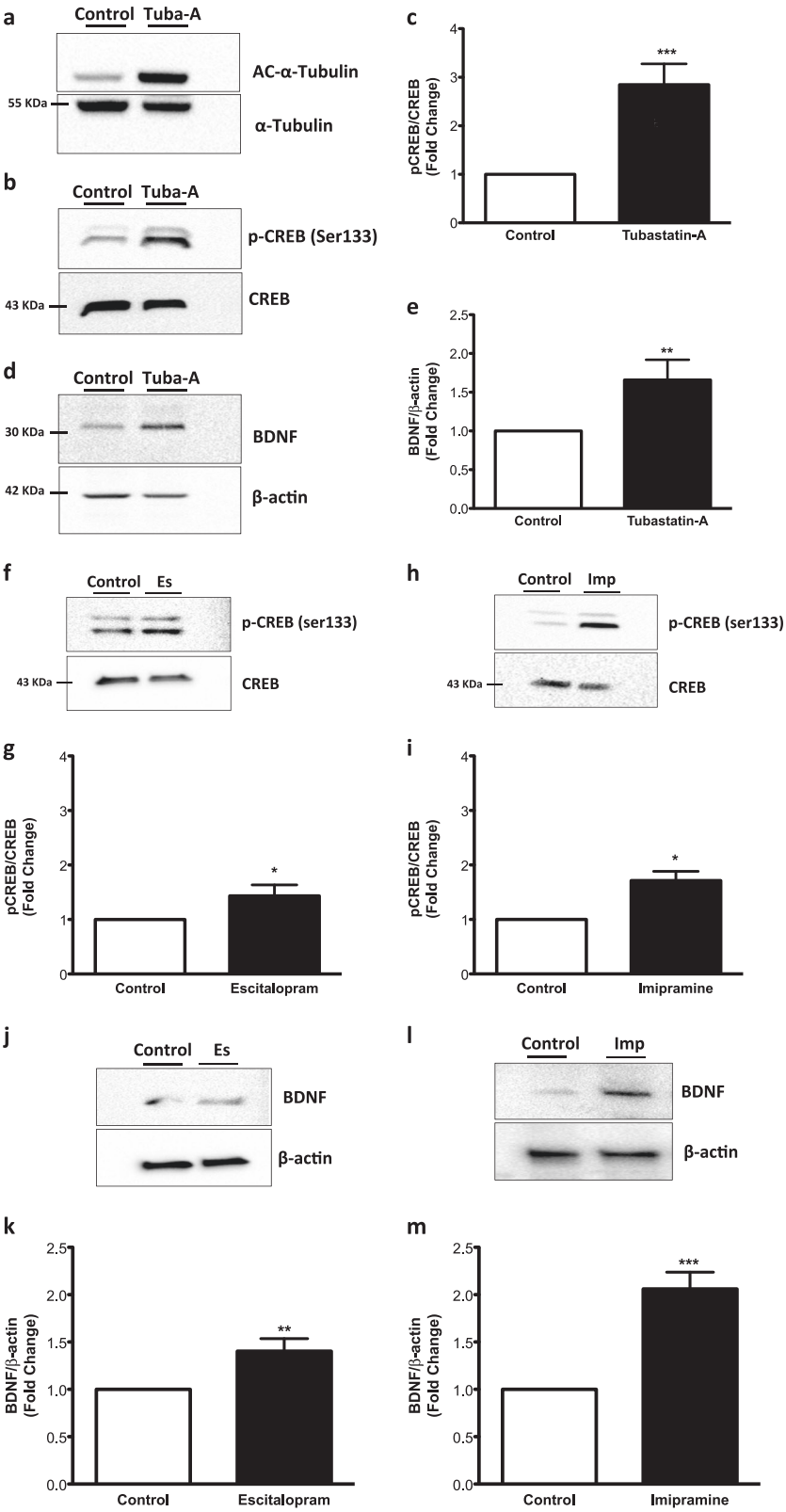


Fig. 4 HDAC6 inhibition and antidepressant treatment activates CREB and induces expression of BDNF. C6 cells were treated with tubastatin-A (10 μM), escitalopram (Es) (10 μM), imipramine (Imp) (10 μM) or vehicle control for 3 days and were collected in lysis buffer. All the samples were probed with anti-acetyl-α-tubulin, total tubulin, anti-phospho-CREB (Ser-133), total CREB, BDNF and β-actin antibodies. The blots shown are representative of three replicate experiments that were quantified for pCREB/CREB **b**, **f**, **h**, or BDNF/β-actin **d**, **j**, **l** and data were plotted as fold change **c**,**e**, **g**, **i**, **k**, **m**. Data are represented as mean ± SEM. Each condition was compared to vehicle control. Data were analyzed using unpaired *t*-test followed by Welch's correction and mean ± SEM are represented as fold change compared to controls. The *p*-values obtained from this test were used for the represented graphs in each figure (**$p < 0.01$ compared to vehicle control; ***$p < 0.001$ compared to vehicle control)

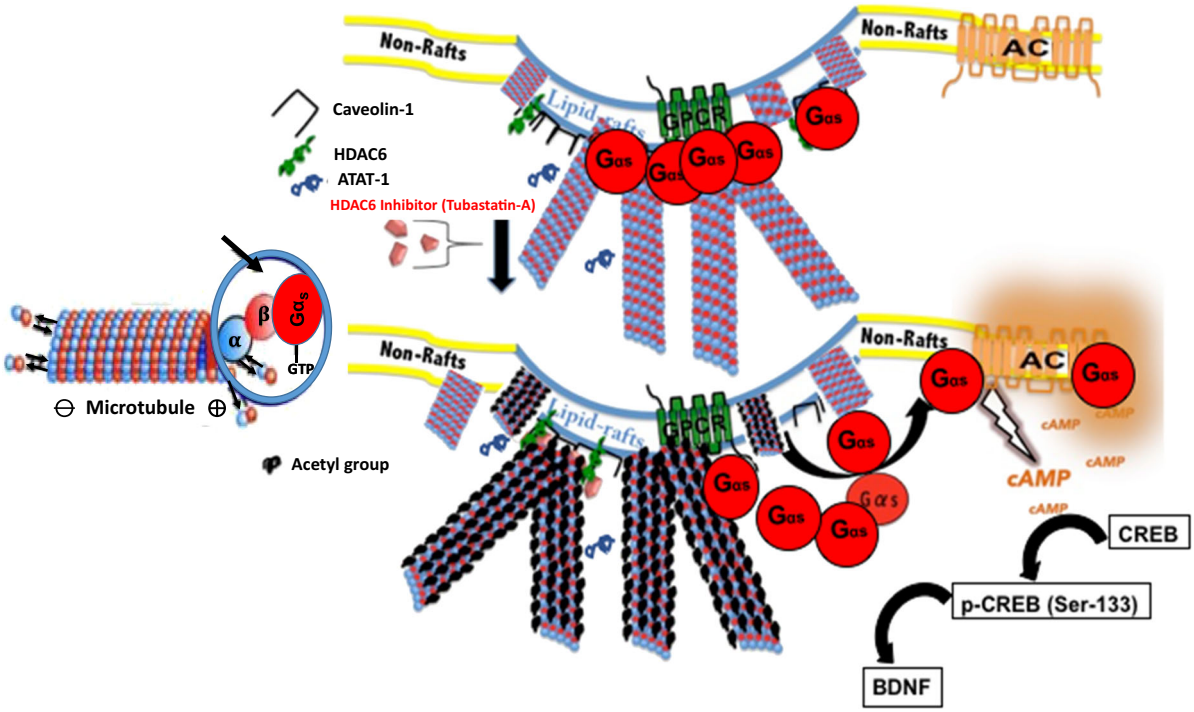


Fig. 5 HDAC6 inhibition disrupts α-tubulin/$G\alpha_s$ complex and lipid-raft membrane localization of $G\alpha_s$ subunit. $G\alpha_s$ associates with tubulin in lipid-raft domains and forms $G\alpha_s$/tubulin complex. We observed that treatment with HDAC6 inhibitor increases acetylation of α-tubulin, resulting in $G\alpha_s$ translocation out of lipid rafts, perhaps as a result of the loss of the tubulin "anchor" in those rafts. This allows greater interaction of $G\alpha_s$ and AC for increased cAMP production. Increased cAMP activates cyclic AMP response element binding protein (p-CREB) and downstream brain derived neurotrophic factor (BDNF). Note that tubulin is depicted as microtubules; however, tubulin in rafts may also exist as dimers, which can bind $G\alpha_s$ [77]

and CREB activation elicits antidepressant-induced BDNF overexpression [76, 78]. Tubastatin-A treatment also showed significant increases in BDNF expression (Fig. 4d).

We demonstrate here that HDAC6 inhibition augments $G\alpha_s$/AC coupling and the sequelae of cAMP-induced changes in a manner similar to other antidepressants, but only HDAC inhibitors increase acetylation of α-tubulin (Fig. 5—Schematic). The identification of novel effects of HDAC6 inhibitors may suggest a new pathway for discovery of advanced antidepressant therapy. Furthermore, the consistency with which different classes of antidepressants translocate $G\alpha_s$ and increase cAMP suggests a reproducible biosignature for antidepressant response that might be exploited for diagnostic and therapeutic purposes.

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ADDITIONAL INFORMATION

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