BDNF-induced recruitment of TrkB receptor into neuronal lipid rafts: roles in synaptic modulation

Shingo Suzuki,1,2,3 Tadahiro Numakawa,4 Kazuhiro Shimazu,6 Hisatsu Koshimizu,1 Tomoko Hara,1 Hiroshi Hatanaka,2 Lin Mei,5 Bai Lu,6 and Masami Kojima1,3

1Research Institute for Cell Engineering, National Institute of Advanced Industrial Science and Technology (AIST), Ikeda, Osaka, 563-8577, Japan
2Institute for Protein Research, Osaka University, Suita, Osaka, 565-0871, Japan
3Solution Oriented Research for Science and Technology, Japan Science and Technology Agency, Kawaguchi, Saitama, 332-0012, Japan
4National Institute of Neuroscience, National Center of Neurology and Psychiatry, Kodaira, Tokyo, 187-8502, Japan
5Institute of Molecular Medicine and Genetics, Medical College of Georgia, Augusta, GA 30912
6Section on Neural Development and Plasticity, NICHD, National Institutes of Health, Bethesda, MD 20892

BRAIN-derived neurotrophic factor (BDNF) plays an important role in synaptic plasticity but the underlying signaling mechanisms remain unknown. Here, we show that BDNF rapidly recruits full-length TrkB (TrkB-FL) receptor into cholesterol-rich lipid rafts from nonraft regions of neuronal plasma membranes. Translocation of TrkB-FL was blocked by Trk inhibitors, suggesting a role of TrkB tyrosine kinase in the translocation. Disruption of lipid rafts by depleting cholesterol from cell surface blocked the ligand-induced translocation. Moreover, disruption of lipid rafts prevented potentiating effects of BDNF on transmitter release in cultured neurons and synaptic response to tetanus in hippocampal slices. In contrast, lipid rafts are not required for BDNF regulation of neuronal survival. Thus, ligand-induced TrkB translocation into lipid rafts may represent a signaling mechanism selective for synaptic modulation by BDNF in the central nervous system.

Introduction

In the central nervous system (CNS), brain-derived neurotrophic factor (BDNF) not only promotes neuronal survival and differentiation, but also regulates synaptic transmission and plasticity. Pharmacological studies demonstrate BDNF enhances the survival of cortical neurons in culture (Ghosh et al., 1994). On the other hand, substantial experiments suggest that a major function of BDNF in the CNS is to regulate synaptic transmission and plasticity (Lu, 2003). In cultured hippocampal or cortical neurons, application of BDNF elicits a rapid potentiation of excitatory synaptic transmission primarily by enhancing presynaptic transmitter release (Lessmann, 1998; Takei et al., 1998). In slices, BDNF facilitates hippocampal long-term potentiation (LTP) and enhances synaptic response to LTP-inducing tetanus (Figurov et al., 1996; Patterson et al., 1996). Both in vitro and in vivo studies demonstrate that BDNF induces complex effects on dendritic arborization of pyramidal neurons (McAllister et al., 1995).

Despite rapid progress in this area, the molecular mechanisms remain ill defined (Lu, 2003). All the functions of BDNF are mediated by TrkB, a receptor tyrosine kinase (RTK; Kaplan and Miller, 2000). Binding of BDNF rapidly activates its tyrosine kinase, which in turn triggers multiple intracellular signaling pathways. Downstream pathways include MAPK, phosphatidylinositol 3-kinase (PI3-K) and PLCγ. A critical yet poorly understood issue is how signals from this receptor are transduced to mediate diverse biological functions in CNS neurons.

One idea for specific signal-function coupling is that different signaling pathways may be transduced in different subcellular compartments. More specifically, it has been proposed that cholesterol/sphingolipid-rich microdomains called lipid rafts make a specialized signaling platform in the plasma membrane, and therefore can transduce signals different from those in the nonraft membrane (Simons and Toomre, 2000; Anderson and Jacobson, 2002). Because both lipid components are resistant to solubilization with nonionic detergents, lipid rafts can be biochemically isolated as detergent-resistant membrane fractions. Raft fractions prepared from brain tissues are enriched in proteins that carry lipid modifications such as...
glycosylphosphatidylinositol (GPI)-anchored proteins, as well as palmitylated or myristoylated proteins such as Src-family kinases and trimeric or small G proteins, suggesting a crucial role of lipid rafts in signal transduction in the CNS (Paratcha and Ibanez, 2002). Recently, lipid rafts have been shown to serve as organizing platforms for chemotrophic guidance of nerve growth cones (Guirland et al., 2004). Transmembrane RTKs, including EGF receptor (Mineo et al., 1999) and FGF receptor (Citores et al., 1999) are associated with rafts. The localization of certain signaling molecules in the rafts allows them to interact with each other more efficiently, and prevents them from interacting with the proteins outside rafts (Simons and Toomre, 2000). Thus, entering and exiting lipid rafts of RTKs represent a unique mechanism that transduces differential signals at the subcellular levels. In the present study, we used brain tissues, slices and dissociated cultures to examine whether TrkB receptor is localized in lipid rafts of the plasma membrane, and if so, how the localization is regulated and what the functional roles are. Our results reveal a BDNF-induced TrkB translocation into the lipid rafts, and such translocation is important for BDNF-induced synaptic modulation in CNS neurons.

Results

**BDNF-induced translocation of TrkB into lipid rafts**

Lipid raft fraction was prepared from tissues or primary cultures of cerebral cortex according to the method of Kawabuchi et al. (2000; Fig. S1A, available at http://www.jcb.org/cgi/content/full/jcb.200404106/DC1). We first examined whether full-length TrkB (TrkB-FL) and its ligand BDNF were localized in lipid rafts at different stages of cortical development. Both proteins exhibit a gradual increase in lipid rafts after birth (Fig. S1B). The components of the lipid rafts, such as cholesterol and raft marker proteins caveolin-2 and Fyn, also increased in rafts during postnatal development (Fig. S1C), raising the possibility that the raft localization of TrkB and BDNF may depend on the developmental expression of these components in rafts. The parallel increase of TrkB and BDNF in lipid rafts also suggests that BDNF may regulate the localization of TrkB in lipid rafts.

To directly test whether BDNF recruits TrkB into lipid rafts, we prepared the rafts in cultured cortical neurons treated with BDNF. In the cortical cultures used here, 93.3 ± 2.4% and 3.8 ± 0.7% are NSE-positive neurons and GFAP-positive astrocytes, respectively (n = 6 independent experiments). As shown in Fig. 1 A, application of BDNF induced an increase in TrkB-FL in the raft fraction. There was a low amount of TrkB-FL in lipid rafts in naïve neurons, suggesting that in naïve cells TrkB-FL may be associated with rafts with a low affinity. In cultures stimulated with 200 ng/ml BDNF for 30 min, the amount of TrkB-FL was markedly increased in rafts (TrkB-FLBDNF-treated/TrkB-FLcontrol = 3.4 ± 0.8-fold, P < 0.03) but decreased slightly in nonrafts (23.1 ± 6.4%). Total proteins in both regions were not changed by the BDNF treatment (Fig. 1 A). When expressed as TrkB-FL/total protein, BDNF increased TrkB-FL in rafts by 3.63 ± 0.73-fold, indicating that BDNF selectively increases the amount of TrkB-FL, but not protein concentration, in rafts.

A time course study demonstrated that the partition of TrkB-FL into rafts was significant at 5 min, peaked at 30–120 min after BDNF application, and returned to control levels within 6 h (Fig. 1 B). The translocation was observed 1 min after BDNF addition (Fig. S2, available at http://www.jcb.org/cgi/content/full/jcb.200404106/DC1). On the other hand, TrkB-FL in nonraft fraction exhibited a gradual decrease after BDNF exposure (Fig. 1 B). BDNF-induced recruitment of TrkB-FL into rafts was dose dependent (Fig. 1 C). To confirm that BDNF selectively translocated TrkB-FL into lipid rafts, we examined whether BDNF stimulation also affects the distribution of other receptors in the rafts and nonraft membrane frac-
A 30-min treatment with BDNF did not change the distribution of Trk, a nontyrosine kinase receptor, or EGF receptor, a tyrosine kinase receptor (Fig. 1 A, left). Together, these data suggest that BDNF rapidly and selectively induces the translocation of TrkB-FL from nonrafts into lipid rafts.

TrkB translocation: dependence on its tyrosine kinase activity

Binding of BDNF to TrkB-FL induces the autophosphorylation of its tyrosine residues on the intracellular kinase domain, leading to its activation (Kaplan and Miller, 2000). To test whether TrkB recruited into rafts is activated, we performed Western blot analysis using anti–phospho-Trk antibody (pY490; Binder et al., 1999). In neurons treated with BDNF for 30 min, a substantial amount of TrkB-FL recruited into rafts was tyrosine phosphorylated (Fig. 2 A, top). In BDNF-treated cultures, TrkB-FL tyrosine phosphorylation relative to total TrkB-FL protein was not significantly different between rafts and in nonrafts (Fig. 2 A, bottom; P > 0.64). To investigate whether activation of TrkB tyrosine kinase was required for the translocation of TrkB-FL into lipid rafts, we performed the following experiments. First, we treated cortical neurons with the Trk kinase inhibitors, K252a or AG879 for 3 h before BDNF stimulation (Fig. 2 B). K252a (100 nM), which reduced BDNF-dependent TrkB tyrosine phosphorylation by 68.8 ± 12.2% in rafts and by 49.4 ± 7.0% in the nonrafts (n = 3 independent experiments), inhibited BDNF-induced TrkB-FL translocation (Fig. 2 B). BDNF-dependent recruitment of TrkB-FL into rafts was also blocked by another Trk kinase inhibitor AG879 (10 μM). Second, because TrkB activation could be induced by a 1-min exposure to BDNF (Takei et al., 1998), we tested whether this short-term stimulation would allow recruitment and partition of TrkB-FL in rafts. Cultured cortical neurons were stimulated with BDNF for 1 min, followed by incubation with medium containing no BDNF for 5–360 min. As shown in Fig. 2 C, a 1-min stimulation with BDNF was sufficient to recruit TrkB-FL into rafts. The amount of TrkB-FL continued to increase after BDNF was washed out, suggesting that once activated TrkB-FL can move into lipid rafts. Third, TrkB-T1, a truncated form of the TrkB receptor lacking tyrosine kinase domain, did not appear to be partitioned into rafts by BDNF (Fig. S3A, available at http://www.jcb.org/cgi/content/full/jcb.200404106/DC1). Finally, NT-4 (200 ng/ml, 30 min), another ligand that activates TrkB tyrosine kinase, recruited TrkB-FL into rafts (Fig. S3 B). Together, these results suggest that BDNF-induced translocation of TrkB into rafts requires its tyrosine kinase activity. Because cultured astrocytes expressed TrkB-T1, but not TrkB-FL (Fig. S3 C), the TrkB-FL translocation is likely to occur in neurons only.

Regulation of BDNF-induced translocation of TrkB into rafts by p75NTR

How is BDNF-dependent translocation of TrkB-FL into rafts regulated? Given that the pan-neurotrophin receptor, p75NTR, associates with lipid rafts (Higuchi et al., 2003) and forms a heterodimer with Trk family receptors (Hempstead, 2002), p75NTR may facilitate BDNF-dependent association of TrkB with rafts. To test this, we introduced p75NTR or lacZ into cortical neurons using adenovirus-mediated gene transfer. As a control, TrkB-FL recruited into rafts is tyrosine phosphorylated. Cortical neurons were treated with (200 ng/ml) or without BDNF for 30 min. (Top) Sample blots. (Bottom) Quantification. pTrkB-FL/total TrkB-FL was quantified in fractions 2 and 6, and shown as relative to that of “−BDNF” in fraction 6. n = 5 preparations from five independent experiments. (B) Inhibition of TrkB-FL activation prevents TrkB-FL translocation into lipid rafts. Neurons were treated with 100 nM K252a or 10 μM AG879 for 3 h, followed by a 30-min stimulation with 200 ng/ml BDNF. (C) Effect of a brief exposure to BDNF on TrkB-FL translocation. Cortical neurons were treated with 200 ng/ml BDNF for only 1 min followed by incubating with medium containing no BDNF for the indicated times. Note that once activated, TrkB-FL continued to be partitioned into rafts in the absence of BDNF.
The location and activation of TrkB-FL in nonrafts are not influenced by p75NTR. Similar results were obtained from two separate experiments.

**Distribution of signaling molecules downstream of TrkB-FL in lipid rafts and nonrafts**

Phosphorylated tyrosine residues on the TrkB intracellular domain form docking sites for the signaling proteins Shc, Grb2, and PLCγ, leading to activation of MAPK (Erks), PLCγ, and PI3-K pathways (Kaplan and Miller, 2000). We tested whether TrkB-FL, upon BDNF stimulation, carries these signaling molecules into lipid rafts during its translocation. In naïve neurons, Erks extended throughout the gradient (fractions 2–5), whereas Shc, Grb2, p85 subunit of PI3-K, Akt, and PLCγ were primarily localized in the bottom, nonraft fraction (Fig. 4 A, left). BDNF application did not increase the amount of any of these proteins in fraction 2 (Fig. 4 A, right), suggesting that TrkB-FL does not carry its associated signaling molecules into lipid rafts during its translocation. When a milder detergent Triton X-165 was used to prepare rafts (Fig. 4 A, left), BDNF application did not increase the amount of any of these proteins in fraction 2 (Fig. 4 A, right), suggesting that TrkB-FL does not carry its associated signaling molecules into lipid rafts during its translocation. When a milder detergent Triton X-165 was used to prepare rafts (Fig. 4 A, left).

**Requirement of lipid rafts for short-term synaptic modulation by BDNF**

What is the functional role of BDNF-induced TrkB translocation into lipid rafts? Because the translocation was observed 1 min after BDNF application (Fig. S2), we reasoned that this process may be involved in the short-term actions of BDNF (Lu, 2003). BDNF has been shown to rapidly enhance transmitter release in cultured cortical neurons (Matsumoto et al., 2001). Therefore, we tested whether disruption of lipid rafts would interfere with BDNF modulation of depolarization-evoked transmitter release at CNS synapses. Methyl-β-cycloexodrin (MCD) binds and depletes cholesterol from the plasma membrane, and thereby disrupts lipid rafts (Simons and Toomre, 2000). A 10-min treatment with MCD (2 mM) removed membrane cholesterol by 33 ± 2% (91 ± 2 ng/well) in control cultures, 61.2 ± 5 ng/well in MCD-treated cultures, n = 4 independent experiments, but did not affect the amount of caveolin-2 and Fyn in lipid rafts (Fig. 5 A, right). Treatment of the cultured cortical neurons with 2 mM MCD significantly attenuated the BDNF-induced recruitment of TrkB-FL into the rafts (Fig. 5 A, left and middle). Consequently, the amount of phosphorylated TrkB was also reduced in the rafts. Importantly, TrkB phosphorylation in the nonraft fraction was not affected. Thus, cholesterol may play a role in TrkB translocation into lipid rafts.

We reported previously that in cultured cortical neurons, pretreatment with BDNF enhanced glutamate release evoked by 4-amino pyridine (4-AP), a K+ channel blocker frequently used in biochemical assays of evoked neurotransmitter release (Matsumoto et al., 2001). As shown in Fig. 5 B, pretreatment with BDNF for 30 min had no effect on the content of glutamate in the medium (white bars in BDNF-pretreated cultures), but significantly enhanced 4-AP–induced glutamate release (hatched bars in BDNF-pretreated cultures). A 10-min treatment with 2 mM MCD before BDNF exposure, however, abolished BDNF enhancement of 4-AP–evoked glutamate release. The neurons pretreated with 2mM MCD alone displayed 4-AP–evoked glutamate release, which was comparable to that in control neurons, indicating that cholesterol depletion itself does not impair the exocytosis machinery. Long-term treatment with raft depleting agents such as fumonisin B1 and mevastatin has been reported to lead to instability of AMPA receptors and loss of dendritic spines and synapses (Hering et al., 2003). In contrast, dendritic parameters (Murphy and Segal, 1996) were not affected by short-term treatment (30 min) with 2 mM MCD. The dendritic diameter was about the same in control cultures and MCD-treated cultures (1.19 ± 0.04 μm in control cultures, 1.18 ± 0.11 μm in MCD-treated cultures, n = 415 segments). Likewise, MCD treatment did not change spine density (spine number per 10 μm dendritic segment; 2.47 ± 0.11 in control cells, 2.36 ± 0.10 in cells treated with 2 mM MCD, n = 945). Furthermore, immunocytochemistry using antibodies against the presynaptic marker synaptophysin and postsynaptic marker PSD95 indicated that short-term MCD treatment did not alter the number or the distribution of synapses (Fig. 5 C). These data support the notion that MCD selectively prevents the rescaling of activated TrkB in lipid rafts, leading to impairments of BDNF modulation of glutamate release.
The biochemical assay described above measures both synaptic and nonsynaptic glutamate release. To determine whether lipid rafts are important for BDNF modulation of neurotransmitter release at synapses, we measured synaptic exocytosis in cultured hippocampal neurons using a style membrane dye FM1-43 (Ryan et al., 1993). A second depolarization of these FM dye-loaded neurons by high K+/H11001 solution (see Materials and methods) resulted in a rapid destaining of the FM dye-labeled spots, reflecting transmitter release at the synapses (Fig. 6, A and B). Pre-treatment with BDNF for 30 min enhanced depolarization-induced FM1-43 destaining (Fig. 6 B). A 10-min treatment with MCD (2 mM) before BDNF application prevented the enhancement effect of BDNF (Fig. 6 C). The neurons pretreated with MCD alone exhibited FM1-43 destaining similar to that in control neurons (Fig. 6 C), indicating that neither uptake nor destaining of FM 1-43 dye was affected by MCD pretreatment.

Similar to the effect of BDNF in hippocampal cultures, BDNF enhanced depolarization-induced FM dye destaining, and MCD attenuated the BDNF effect, in cultured cortical neurons (Fig. 6 D). Several experiments were performed to ensure that the MCD effect was due specifically to removal of cholesterol and disruption of lipid rafts, rather than to a nonselective, pharmacological effect such as removal of proteins from the plasma membrane. First, we pretreated the cultures with 50 ng/ml filipin, a cholesterol sequestration agent with a structure distinct from that of MCD (Simons and Toomre, 2000; Ma et al., 2003). We found that, although FM 1-43 uptake appeared to be
slightly lower, filipin, like MCD, completely reversed the effect of BDNF on depolarization-induced FM dye destaining (Fig. 6 E). Neurons pretreated with filipin alone exhibited FM dye destaining similar to that in control neurons (Fig. 6 E). Second, if the MCD effect were due to a nonspecific removal of membrane protein, addition of MCD–cholesterol complex should not rescue the deficits induced by MCD. We treated the cultures with MCD–cholesterol complex (1 mg/ml MCD balanced with 40 \mu g/ml cholesterol) for 10 min (Thiele et al., 2000). Remarkably, this treatment did not affect the potentiating effect of BDNF on depolarization-induced destaining of FM 1-43 (Fig. 6 D). We therefore conclude that lipid rafts are important for the modulation of neurotransmitter release and synaptic exocytosis by BDNF.

One of the major functions of BDNF in the intact hippocampal synaptic circuits is to attenuate synaptic fatigue induced by a train of high frequency stimulation (HFS; or tetanus, 100 Hz, 1 s; Figurov et al., 1996). We next examined the role of lipid rafts in this form of synaptic modulation. In neonatal hippocampal slices (P12-13) in which the level of endogenous BDNF is low, application of tetanus resulted in pronounced synaptic fatigue at Schaffer collateral-CA1 synapses (Fig. 7 A). Consistent with our previous reports (Figurov et al., 1996), treatment with exogenous BDNF (2 nM) for 1–2 h significantly attenuated the synaptic fatigue (Fig. 7 B). However, pretreatment with MCD for 30 min completely abolished the attenuating effect of BDNF on HFS-induced synaptic fatigue. Quantitative analysis indicated that treatment with BDNF markedly increased the rate constant (τ) for synaptic fatigue and disruption of lipid rafts with MCD completely prevented such an increase (Fig. 7 C). It is important to note that treatment with MCD for 3 h had no effect on synaptic responses to HFS (Fig. 7, B and C), nor did MCD affect basal synaptic transmission or tetanus induced LTP (Ma et al., 2003). These results suggest that short-term exposure to MCD per se does not affect the number of readily releasable vesicles in the presynaptic terminals or the number or properties of AMPA or NMDA receptors on the postsynaptic density.

Requirement of lipid rafts for long-term regulation of dendritic growth, but not neuronal survival, by BDNF

To test whether lipid rafts are also involved in long-term effects of BDNF, we treated cultures with cholesterol synthesis inhibitors, mevastatin or pravastatin, which effectively deplete rafts from cortical neurons over days (Hering et al., 2003). The cholesterol level was significantly reduced in mevastatin- or pravastatin-treated cortical neurons (Fig. 8 A). We first exam-
ined the effect of these lipid raft disrupters on BDNF regulation of neuronal survival, using the WST-1 assay, which quantitatively determines cell viability based on the cleavage activity of a soluble tetrazolium salt WST-1 by mitochondrial dehydrogenases, and by counting the number of MAP2-positive neurons in culture. 3-d treatment with BDNF significantly enhanced the survival of cortical neurons in serum-free medium (Fig, 8, B and C, left; Yamada et al., 2001). Both mevastatin and pravastatin, however, failed to block this effect of BDNF (Fig. 8, B and C, middle and right), indicating that lipid rafts are not required for the regulatory effect of BDNF on cortical neuron survival.

BDNF has also been shown to be a potential regulator for dendritic growth of CNS neurons (McAllister et al., 1995). We next examined whether lipid rafts are important for BDNF regulation of dendritic growth. 3-d exposure of BDNF led to robust growth of MAP2-positive primary dendrites (Fig. 8 D, BDNF). Quantitative analysis revealed that BDNF increased the number of primary dendrites by >50% (P < 0.001). This effect of BDNF, however, was effectively blocked by mevastatin, whereas treatment with mevastatin alone had no effect (Fig. 8 D). Thus, while required for short-term modulation of synaptic transmission and plasticity by BDNF, lipid rafts may mediate some, but not all long-term effects of BDNF in CNS neurons.

**Discussion**

One of the conceptually difficult issues in neurotrophin research is how a single neurotrophin could elicit different effects under different conditions on the same neurons, or on certain parts of the same neurons (Bibel and Barde, 2000). How could, for example, BDNF regulate synaptic transmission without altering the survival of neurons of adult cortex? One way to ensure signaling specificity is to induce BDNF signaling in specific subcellular compartments. In the present study, we demonstrated that BDNF stimulation induced the translocation of activated TrkB-FL from nonrafts to lipid rafts in cortical neurons. We further showed that attenuation of such translocation by depleting cholesterol in the lipid rafts prevented the effects of BDNF on synaptic transmission and plasticity, but not neuronal survival. These results reveal a new mechanism for the signaling specificity of BDNF, and suggest a critical role of lipid rafts in the synaptic function of BDNF in CNS neurons.

**BDNF-induced translocation of activated TrkB into lipid rafts**

One of the key findings in the present study is that TrkB translocation to rafts depends on its tyrosine kinase activity. This notion is supported by a number of observations: (a) inhibition of the TrkB kinase activity by K252a or AG879 significantly inhibited BDNF-induced translocation of TrkB-FL; (b) NT-4, which activates the TrkB RTK, also induced TrkB-FL translocation; (c) 1-min exposure of BDNF, which activates TrkB, was sufficient to partition TrkB-FL into rafts. Thus, TrkB activation has to occur before the translocation; and (d) TrkB-T1, the truncated form of TrkB lacking the tyrosine kinase domain, was not recruited into rafts by BDNF. This last result, however, has to be interpreted with caution. It is also possible that the intracellular domain of the TrkB receptor may contain motifs that interact with other proteins important for the delivery of TrkB to the lipid rafts.

Another important observation is that removing of cholesterol, a major component in the lipid rafts, with 2 mM MCD inhibited TrkB signaling, leading to impairments in synaptic transmission and plasticity. The most straightforward interpretation is that MCD disrupted BDNF-induced translocation of TrkB-FL into rafts, and consequently impaired TrkB signaling.
in rafts. Alternatively, TrkB may need to interact with cholesterol to become fully functional, and therefore depletion of cholesterol directly affects TrkB signaling, rather than TrkB translocation. Consistent with this idea, BDNF failed to induce TrkB phosphorylation on the cell surface in cultured striatal neurons from Niemann-Pick type C mice (NPC−/−), which have abnormal cholesterol metabolism (Henderson et al., 2000). The fact that there was a small amount of TrkB in lipid rafts in naïve cells (Fig. 1A) also supports the idea that TrkB interacts with rafts, perhaps with a low affinity. However, several observations argue against this idea. First, in cultured striatal neurons from NPC−/−, the content of free cholesterol was normal, suggesting that the cholesterol-rich microdomains on cell surface are probably normal. Thus, the dysfunction of TrkB on cell surface in NPC−/− is probably due to reasons other than lack of cholesterol in the plasma membrane. Second, we demonstrated that treatment with 2 mM MCD, which removed membrane cholesterol by 33%, interfered with TrkB recruitment into rafts, but not TrkB activation outside rafts (Fig. 5A). The basal level of TrkB localization in rafts in resting cells was normal as well. Finally, treatment with 10 mM MCD, which removed >95% cholesterol, did not diminish TrkB kinase activity (Fig. S5, available at http://www.jcb.org/cgi/content/full/jcb.200404106/DC1). These data suggest that cholesterol is involved in the recruitment of TrkB into lipid rafts, but not directly in TrkB function.

A third possible mechanism for TrkB translocation is that BDNF signaling involves an interaction between TrkB and protein X, which could be a protein embedded in cholesterol-rich membranes. Cholesterol depletion could in principle lead to structural changes in the protein X (Simons and Toomre, 2000; Munro, 2003; Glebov and Nichols, 2004), and therefore disturb its interaction with TrkB. Although the nature of protein X remains unknown, we tested whether p75NTR, which is primarily associates with rafts (Higuchi et al., 2003) and is capable of binding to Trk receptors (Hempstead, 2002), facilitates BDNF-dependent translocation of TrkB into rafts. Interestingly, expression of exogenous p75NTR in cortical neurons inhibited TrkB translocation into lipid rafts, as well as the level of TrkB phosphorylation in the rafts, but not the basal association of TrkB with rafts or TrkB phosphorylation outside rafts (Fig. 3). These data are opposite to the above prediction and suggest that p75NTR has an inhibitory function in TrkB translocation and lipid raft-mediated BDNF/TrkB signaling. Thus, although it is unlikely that BDNF-induced TrkB translocation into lipid rafts is mediated by p75NTR through its interaction with TrkB, our experiments could not rule out the possibility that a protein X is an intermediate for BDNF-induced TrkB translocation into rafts.

The dynamic behavior of TrkB into lipid rafts is most analogous to that of two tyrosine kinase receptors, c-Ret for glial cell line–derived neurotrophic factor (GDNF; Tansey et al., 2000; Paratcha et al., 2001) and ErbB4 for neuregulin (Ma et al., 2003). c-Ret is recruited into lipid rafts upon GDNF stimulation by two distinct mechanisms. In cells expressing c-Ret and GPI-anchored protein GFRα1 (GDNF family receptor α1), which is primarily associated with lipid rafts, the binding of GDNF to GFRα1 results in a transient recruitment of c-Ret into the compartment. Unlike TrkB translocation, this movement is independent of the kinase activity. In cells lacking GPI-anchored GFRα1, however, coapplication of GDNF and soluble GFRα1 allows stabilization of c-Ret in rafts, and this effect is tyrosine kinase-activity dependent. These mechanisms lead to the association of c-Ret with different adaptor proteins.
Role of BDNF-dependent TrkB translocation into lipid raft in synaptic modulation

The present study has revealed the importance of TrkB translocation into rafts in short-term modulation of synaptic transmission and plasticity by BDNF. In contrast, lipid rafts are not required for BDNF regulation of cortical neuron survival. In neurons, lipid rafts are preferentially distributed in synaptic membranes (Ma et al., 2003). In cerebral cortex in vivo, TrkB-FL is present in lipid rafts (Fig. S1 B). Moreover, the endogenous BDNF appears to be enriched in lipid raft fractions in the adult cortex (Fig. S1 B), stored in vesicles in synaptosomes (Fawcett et al., 1997), and secreted at synapses in an activity-dependent manner (Hartmann et al., 2001; Kojima et al., 2001). Thus, the translocation of TrkB into lipid rafts may imply a BDNF-induced recruitment of TrkB into the synapses.

Because BDNF elicits the synaptic effects through presynaptic mechanisms (Gottschalk et al., 1998; Lessmann, 1998), activated TrkB may need to be translocated to the rafts in the presynaptic terminals to interact with its target molecules. The specific target molecules mediating the presynaptic effects of BDNF, however, remain to be fully identified. In purified nerve terminals (synaptosomes) from cerebral cortices, application of BDNF facilitates evoked glutamate release and increases the MAPK-dependent phosphorylation of synapsin I, a synaptic vesicle-associated protein implicated in the control of transmitter release (Jovanovic et al., 2000), suggesting a critical role in the TrkB/MAPK/synapsin signaling cascade. BDNF also rapidly induces MAPK phosphorylation in these slices and inhibition of MAPK signaling blocks BDNF modulation of

proteins inside rafts and elicit neuronal survival and differentiation. Similar to TrkB-FL, ErbB4 is recruited into lipid rafts by neuregulin. However, it is unclear whether ErbB4 translocation depends on its kinase activity. Although neuregulin translocates the whole receptor complex, including ErbB4 and its adaptor proteins, such as Grb2 and Shc, into rafts, BDNF recruited TrkB alone into lipid rafts, without carrying its associated proteins Shc, Grb2, and PLCγ (Fig. 4 A and Fig. S4 A). However, we cannot completely rule out the possibility that the movement of these associated proteins into rafts was under the detection limit of our immunoblotting analysis. Given that Shc, Grb2, Erks, and PLCγ were present in lipid rafts in an experiment using a milder detergent Triton X-165 (Fig. S4 A), it is possible that the movement of TrkB-FL into rafts allows TrkB to interact with signaling molecules inside the rafts, a step crucial in transmitting lipid raft-mediated BDNF/TrkB signal transduction.

The raft localization of detergent insoluble proteins including RTKs depends on cell type and detergent stringency (Pike, 2003; Schuck et al., 2003). For example, when a less stringent detergent (Triton X-165) was used, a larger amount of TrkB-FL was associated with rafts in naïve cells, and BDNF-induced movement of TrkB-FL from nonrafts to rafts became less apparent (Fig. S4 B). In PC12 cells, both TrkA and p75NTR are constitutively localized in caveolae/lipid rafts (Bilderback et al., 1999; Huang et al., 1999) and NGF binding does not alter the partition of TrkA and p75NTR in lipid rafts (Huang et al., 1999). This may be due to the specific cell types they are expressed or their association with lipid raft-anchored proteins.
Slice preparation and electrophysiology

Recording of hippocampal slices, prepared from neonatal rat (P12-13), was described previously (Figurov et al., 1996). Field EPSPs were evoked in CA1 stratum radiatum by stimulating Schaeffer-commissurals and were recorded with ACSF-filled glass pipettes (−5 MΩ). Only slices exhibiting EPSPs of 2–3 mV in amplitude without superimposed population spikes were used. Stimulus intensity was adjusted to evoked EPSPs of −1.3 mV. A train of HFS (100 Hz, 1 s) was used to induce synaptic depression. All experimental data were collected at least 10 min after stable EPSPs were achieved. Slices were treated with MCD (2 mM) or BDNF (2 mM) or them together for 2 h before synaptic responses to HFS were tested.

Assays of cell survival and dendritic growth

Cortical neurons (5 x 10^4 cells/cm²) were cultured in Neurobasal medium containing B27 supplement (GIBCO BRL), 0.5 mM glutamine, for 3 d, and treated with indicated agents in Neurobasal medium containing no B27 supplement for 3 d. Cell survival was quantified by WST-1 assay, which determines cell viability based on the cleavage activity of a soluble tetrazolium salt WST-1 by mitochondrial dehydrogenases. In brief, cultured cortical neurons were incubated with a tetrazolium salt WST-1 (Roche) for 30 min and viable cells were then determined by a microplate reader at 450 nm with 650 nm as a reference wavelength. Alternatively, the number of MAP2-positive neurons was counted (Yamada et al., 2001). To identify primary dendrites from each neuron, cells were stained with anti-MAP2 antibody, followed by DAPI staining. After taking images of MAP2-positive neurons with cell body diameters (16.9 ± 0.5 μm, n = 32 cells from four independent coverslips), the number of the primary dendrites was counted.

Online supplemental material

Fig. S1 shows localization of TrkB and BDNF in lipid rafts during cortical development. Fig. S2 shows association of TrkB-FL with lipid rafts 1 h after BDNF stimulation. Fig. S3 shows TrkB-T1 expression in rafts and non-rafts and NTF4-induced recruitment of TrkB-FL into lipid rafts. Fig. S4 shows association of signaling molecules and TrkB with lipid rafts. Fig. S5 shows that treatment with 10 mM MCD lead to a partial decrease in BDNF-induced activation of TrkB-FL. Further comments on the data reported can be found in the legends. Online supplemental material is available at http://www.jcb.org/cgi/content/full/jcb.200404106/DC1.

We thank Dr. Masato Okada for advice on lipid raft preparation, Drs. James Zheng and Eero Castrén for helpful discussion, and Sumitomo Pharmaceuticals for providing recombinant BDNF.

Submitted: 26 April 2004
Accepted: 19 October 2004

References


aptic modulation of synaptic transmission and plasticity by brain-derived neurotrophic factor in the developing hippocampus. *J. Neurosci.* 18: 6830–6839.


