Microtubules provide directional cues for polarized axonal transport through interaction with kinesin motor head

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Post-Golgi carriers of various newly synthesized axonal membrane proteins, which possess kinesin (KIF5)-driven highly processive motility, were transported from the TGN directly to axons. We found that KIF5 has a preference to the microtubules in the initial segment of axon. Low dose paclitaxel treatment caused missorting of KIF5, as well as axonal membrane proteins to the tips of dendrites. Microtubules in the initial segment of axons showed a remarkably high affinity to EB1–YFP, which was known to bind the tips of growing microtubules. These findings revealed unique features of the microtubule cytoskeletons in the initial segment, and suggested that they provide directional information for polarized axonal transport.

Introduction

Neurons are highly polarized cells with dendrites and a long axon. Intracellular transport of various kinds of membrane organelles and protein complexes are fundamental for neuronal morphogenesis, function, and survival. Recently, it has been revealed that a number of kinesin super family proteins (KIFs) play significant roles on these transports (Hirokawa, 1998). Axons in long tracts are as long as 1 m in humans, constituting more than 99% of the volume of the cells. In contrast, the diameter of an axon at a cell body of a mature neuron is often very small, and accordingly, axonally transported materials should be propelled from the cell body to the range only 0.25% of all the directions in order to enter the axon if we assume that the diameter of an axon is one-tenth of that of the cell body. Thus, it is natural to assume that there will be a molecular mechanism for the axonal vesicles to find a way to axons, but it was unknown even whether such selective polarized axonal transport exists within the cell body, and current models for polarized transport in neurons underestimate it (Jareb and Banker, 1998; Burack et al., 2000). Previously, we have shown that the transport of newly synthesized proteins from Golgi complexes to the cell surface is mediated by tubulovesicular organelles in axons, which was subsequently confirmed in both neurons (Nakata et al., 1998; Zakharenko and Popov, 1998; Ahmari et al., 2000; Kaether et al., 2000) and nonneuronal cells (Hirschberg et al., 1998; Toomre et al., 1999). However, it was difficult to analyze the transport within the cell body at high spatial and temporal resolution because of high background due to the ER retention or the overexpression of the protein. Thus, the behavior of post-Golgi axonal and dendrite carriers has not been visualized within the cell body in detail, which is critical for building models for polarized transport in neurons. In this paper, we overcame these difficulties by the improvement of marker proteins and critical angle fluorescence microscopy (CAFM), which enables us to observe inside cells deeper than with the strict total internal reflection (TIR) microscopy and to eliminate most of the background signals. We demonstrated the evidences that axonal post-Golgi carriers in the cell body know the direction of the axon and microtubules (MTs) provide the directional cues for the polarized axonal transport.

Results

Polarized axonal transport in neurons

Previously, axonally transported vesicles were considered to be transported nonselectively into both dendrites and axons because vesicles, which carry axonal membrane protein–GFP

Abbreviations used in this paper: CAFM, critical angle fluorescent microscopy; CLSM, confocal laser scan microscopy; IS, initial segment of axon; MAP, MT-associated protein; MT, microtubule; TIR, total internal reflection; VSV-G, vesicular stomatitis virus G-protein.

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Figure 1. Post-Golgi transport of axonal and dendrite carriers in hippocampal neurons visualized by CLSM. (a) Sorting of membrane protein–GFP fusion proteins under specific cell manipulation. VSVtsO45-G::GFP localizes in the ER at 39.5°C and moves to the TGN after a 30-min incubation at 19.5°C. Its post-Golgi transport starts when the temperature is shifted to 37°C. Note that VSV-G::GFP carriers are predominantly transported to one neurite (arrows) among the others. Kv2.1::GFP distributes diffusely in the somatodendritic area when expressed overnight in the presence of 1 μM brefeldin A. Kv2.1::GFP accumulates at the Golgi region 1 h after the brefeldin A washout, and starts post-Golgi transport. Note that Kv2.1::GFP was transported to all the dendrites 3 h after wash. (b) Characterization of VSV-G::GFP(YFP) probes in neurons. (b1) Neurons were infected with Ad(VSVtsO45-G::GFP) and incubated overnight at 39.5°C, for 30 min at 19.5°C, and for 1 h at 37°C in the presence of 1 mg/ml Texas-red dextran (MW3000). Note that post-Golgi VSV-G carriers in the axon (arrows, green) are not labeled with the endocytic marker (red). (b2 and b3) Double-label of hippocampal neuron with VSV-G::YFP and Golgi–CFP. At 19.5°C (b2), VSV-G::YFP (b2, green) was colocalized with the Golgi complex marker (b2, red) in the cell body. When the temperature is shifted to 37°C (b3), VSV-G::YFP moves from the complex membrane area (yellow area at the upper right of b2, due to the overlap of VSV-G::YFP [green] and Golgi–CFP [red]) to the axon (b3, arrows). (c) VSV-G::GFP was dominantly transported from the TGN to the axon (arrow). Neurons were infected with Ad(VSVtsO45-G::GFP) and incubated overnight at 39.5°C, for 30 min at 19.5°C, and for 1 h at 37°C to visualize post-Golgi membrane transport (green). After fixation, the dendrites were stained with the anti-MAP2 antibody (red). Bar, 50 μm. Videos 1 and 2 are available at http://www.jcb.org/cgi/content/full/jcb.200302175/DC1. (d) Post-Golgi axonal carriers of VSV-G::GFP transport various membrane proteins. Axonally transported tubulovesicular organelles were simultaneously double-labeled with CFP- and YFP-tagged proteins, and time-lapse data were collected by sequential activation with 442 and 488 nm lasers by CLSM. (d1) VSV-G::CFP::CFP (red) and GAP-43::YFP (green). (d2) VSV-G::CFP::CFP (red) and β-APP::YFP (green). (d3) VSV-G::YFP (green) and Vamp2::CFP (red). (d4) Vamp2::CFP (red) and GAP-43::YFP (green). (d5) Vamp2::CFP (red) and β-APP::YFP (green). In each set, interval between the right and left panel is 10 s. Slight gaps between the CFP and YFP images along the longitudinal axis of vesicles are due to the time lag (~0.7 s) between the sequential data acquisition. (e and f) Dominant negative kinesin (S205A;H206A; stained with the H2 antibody; red) inhibits polarized axonal transport of VSV-G::GFP (e, green), whereas it does not inhibit significantly dendritic transport of Kv2.1::GFP (f, green). Bars, 10 μm. (g) Inhibition of polarized axonal transport by dominant negative kinesins. Black bars indicate percentage of neurons with polarized VSV-G::GFP transport, and white bars indicate percentage of neurons exhibiting accumulation of VSV-G::GFP at TGN. Data were collected from four independent cultures.

fusion proteins often accumulated in both dendrites and axons (Jareb and Banker, 1998). This may be due to a small amount of missorted proteins, which finally accumulated at the time of observation in the somatodendritic area with a limited volume because they cannot be exocytosed to dendrite membranes. To eliminate these effects, we used temperature-sensitive vesicular stomatitis virus G-protein (VSV-G tsO45; Hirschberg et al., 1998; Toomre et al., 1999). We expressed VSV-GtsO45::GFP at 39.5°C overnight, allowed it to accumulate in the Golgi apparatus by decreasing the temperature to 19.5°C, and monitored the post-Golgi transport at 37°C (Fig. 1 a; Videos 1 and 2, available at http://www.jcb.org/cgi/content/full/jcb.200302175/DC1). Double label with Golgi–CFP (CLONTECH Laboratories, Inc.) and VSV-G::YFP revealed that VSV-G::YFP colocalized with the Golgi complex–marker at 19.5°C (Fig. 1, b2), and post-Golgi VSV-G::YFP carriers moved predominantly to one neurite from the Golgi region after temperature shift to 37°C (Fig. 1, b3, arrows). This temperature shift protocol was used for VSV-G throughout the experiment. These carriers were not labeled with endocytic marker Texas red dextran (Fig. 1, b1, arrows). This result, together with previous papers, indicates that these carriers are not derived from endosomes (Nakata et al., 1998; Ahmari et al., 2000). Although VSV-G itself is sorted to dendrites (Dotti and Simon, 1990), we found that VSV-G tsO45 was sorted to axons in hippocampal neurons when tagged with GFP in its COOH terminus as shown by staining of dendrites with anti–MT-associated protein (MAP) 2 antibody (Fig. 1 c). Thus, we used VSV-G::GFP as an axonal transport marker. Simultaneous expression of CFP and YFP fusion proteins revealed that VSV-G::GFP was transported by the tubulovesicular organelles, which transport a number of newly synthesized axonal membrane proteins such as β-APP, GAP-43, and vamp-2 (Fig. 1 d), indicating that VSV-G tsO45::GFP labels major post-Golgi carriers for various axonal membrane proteins (Nakata et al., 1998).
VSV-G::GFP was transported in a polarized manner in ~60% of neurons (Fig. 1 g and Fig. 5 j), indicating that there is a mechanism for polarized vectorial axonal transport.

Next, we compared the polarized axonal transport with dendrite transport within the cell body. Because the construct with longer spacers is reported to reduce the effect of GFP tagging on VSV-G sorting in MDCK cells (Keller et al., 2000), we tried the same construct to test whether it could be a marker for dendrite transport. However, its effect was insufficient in the neurons, and a considerable amount of the protein was still sorted to axons (unpublished data). We used Kv2.1::YFP, a potassium channel that is sorted to somatodendritic plasma membrane (Lim et al., 2000), in order to visualize individual post-Golgi dendrite carriers. Among the number of channels and receptors we tried, most of which showed considerable amount of ER retention, which obscured the observation of the post-Golgi dendrite transport, Kv2.1::YFP was accumulated in the Golgi region by brefeldin A washout treatment (Fig. 1 a), which enabled us to follow the subsequent post-Golgi transport. Brefeldin A washout procedure did not affect on sorting as well as the time course of distribution of Kv2.1::YFP within dendrites and used in Fig. 1 a and Fig. 2 (a–e).

Simultaneous expression of VSV-G::CFP::CFP and Kv2.1::YFP showed markers are properly targeted to axonal and dendrite carriers while they are colocalized in the Golgi region (Fig. 2 f). We used CAFM (see Materials and methods), which enabled us to visualize small dim dendrite vesicles that our confocal laser scan microscopy (CLSM) system could not visualize. Our CAFM image of biased axonal transport of VSV-G was fully consistent with the CLSM image. Intense staining in the center of the cell body in Fig. 2 (a and b) are the basal surface of the Golgi region demonstrating the depth of CAFM image from the caverslip. We found that VSV-G carriers were tubular and vesicular in shape, highly motile with long processivity, and preferentially transported to axons (Fig. 2 a; Video 3, available at http://www.jcb.org/cgi/content/full/jcb.200302175/DC1), whereas Kv2.1 carriers were vesicular in shape, less motile with short processivity, and evenly distributed within the cell body (Fig. 2 b; Video 4, available at http://www.jcb.org/cgi/content/full/jcb.200302175/DC1). Comparison of percentage of the carriers with >1 μm displacements in 10 s showed that VSV-G carriers have much higher motile activity than Kv2.1 carriers (Fig. 2 c), which results in the smaller number of VSV-G carriers remaining in the cell body (Fig. 2 d). These differences are not due to the time-lapse imaging at a 5-s interval, as the time-lapse video with a 0.5-s interval (Video 5, available at http://www.jcb.org/cgi/content/full/jcb.200302175/DC1) showed the same tendency of Kv2.1 carrier movements.

Next, we compared the run-length of each 100 individual carriers before they stop or change the direction of movements (Fig. 2 e). We found ~50% of VSV-G carriers show >5 μm processive movements, whereas >50% of Kv2.1 carriers show <1 μm processivity. Given the average run-length of single kinesin motor proteins ~0.6 μm (Vale et al., 1996), the data indicate that multiple active motors are associated with a single VSV-G carrier. This motile property of VSV-G carriers will be suitable for the polarized axonal transport because once the carriers choose the axonal MTs, they will continue to translocate along them until they get out of the cell body.

KIF5 has been shown to transport VSV-G::GFP (Kreitzer et al., 2000), β-APP (Kaether et al., 2000; Kamal et al., 2000), and GAP-43 (Ferreira et al., 1992). We confirmed it by the dominant negative approach. When the full length of KIF5 with mutations at both S205A and H206A, which dissociates kinesin from MTs, is overexpressed in hippocampal neurons, transport of VSV-G::GFP from the TGN was inhibited (Fig. 1, e and g). Rigor-KIF5 (T93N) also inhibited the transport, whereas overexpression of wild-type kinesin did not (Fig. 1 g). In contrast, transport of Kv2.1::YFP was not significantly affected by the dominant negative KIF5
construct (Fig. 1 f). These results, together with previous reports (Ferreira et al., 1992; Kaether et al., 2000; Kamal et al., 2000; Kreitzer et al., 2000), indicate that conventional kinesin is the motor for the axonal transport of tubulovesicular organelles containing VSV-G·GFP.

Sorting of kinesin in neurons

Because our observation suggested that VSV-G carriers are driven by a number of active KIF5 motors, we tested whether KIF5 itself has a property to find its preferential way to the axons. When the full-length KIF5·GFP fusion protein was expressed in hippocampal neurons, a considerable amount of KIF5·GFP was localized in the cell body and dendrites (Fig. 3 a; see Fig. S1 for double label image with axonal marker, available at http://www.jcb.org/cgi/content/full/jcb.200302175/DC1), consistent with the immunocytochemical localization of kinesin (Kanai et al., 2000). Simple localization of kinesin does not reveal the actual site of action of kinesin because recent studies showed that most of the kinesins remains inhibited from binding to MTs by the association of its motor domain with its tail domain (Coy et al., 1999; Hackney and Stock, 2000), and unbound kinesin will be subject to simple diffusion. We eliminated the effect of tail inhibition as well as cargo binding, by deleting the tail and COOH-terminal region of the rod domain (Seiler et al., 2000). The localization of tailless motor proteins can be attributed simply to their motor activity. In fact, these motors are shown to accumulate at the tips of processes (Seiler et al., 2000). Although MT polarity is mixed in the proximal area of dendrites, it is plus end–directed in both the axons and distal parts of dendrites (Baas et al., 1988). If motor proteins do not discriminate MTs, they will run on both axonal and dendritic MTs toward the plus ends, and should accumulate at both axon and dendrite tips. When the tailless KIF5B·GFP fusion protein was expressed, the protein accumulated at the tips of axons, with a marked decrease in its level in dendrites (71 of 84 transfected neurons; Fig. 3 b; see Fig. S1 b for double label image with CFP). Total amount of GFP motor in axonal tips shown in Fig. 3 b was 3.14-fold higher that in the whole dendrites. This was confirmed in all the members of the KIF5 subfamily (KIF5A-C) in mouse. Various KIF5s proteins are involved in axonal versus dendrite transport (Miki et al., 2001). We found that KIF17, an MT-plus end–directed motor transporting glutamate receptor NR2B in dendrites (Setou et al., 2000), accumulated at the tips of both dendrites and axons when their tail domains were deleted (41 of 47 tailless KIF17 transfected neurons; Fig. 3 c; see Fig. S1 c for double label image with dendrite marker). The accumulated KIFs were extracted by mild saponin extraction in the presence of paclitaxel without ATP (unpublished data), indicating that their accumulation is not due to strong binding to MTs in the distal (Nakata and Hirokawa, 1995). Chimera proteins with the KIF5 head and KIF17 neck and rod accumulated at the tips of axons (Fig. 3, d and j), whereas chimera proteins with KIF17 head and KIF5 neck and rod accumulated in both axons and dendrites (Fig. 3, e and j), indicating that the motor domain is a key to determine the KIF5 preference to axons. Motility of these chimera proteins was verified by in vitro motility assay (Fig. S2, available at http://www.jcb.org/cgi/content/full/jcb.200302175/DC1).

Next, we overexpressed chimera protein of the KIF17 head and KIF5 neck to tail domain in hippocampal neurons, and examined its effect on polarized axonal transport. In neurons, which overexpress full-length KIF5, polarized axonal transport was maintained (Fig. 3 f). Video 6 shows the VSV-G·GFP transport in the neuron presented in Fig. 3 f (Video 6, available at http://www.jcb.org/cgi/content/full/jcb.200302175/DC1). In contrast, when KIF17-KIF17 chimera protein was expressed, axonal carriers were transported in both axons and dendrites (Fig. 3 g; Video 7, available at http://www.jcb.org/cgi/content/full/jcb.200302175/DC1). The results suggest that the preferential axonal transport is attributed to the KIF5 motor domain. In contrast, tailless motor experiment indicates that motor domain preference does not explain the exclusion of dendrite carriers from axons because both tailless KIF5 and KIF17 were accumulated at the tips of axons. Indeed, NR2B·YFP was not missorted to axons when coexpressed with KIF5 head and KIF17 rod and tail construct (Fig. 3, h and i). Although KIF5 head has preference in axons and KIF17 head also can enter the axons, if there is a mechanism such as their cargo dissociates.

Figure 3. Tailless motors were destined for different regions of neurons. Data were obtained by CLSM. (a) Full-length KIF5B·GFP was transfected into hippocampal neurons. It was distributed throughout the cell body, dendrites, and the axon (arrows). The cell body and dendrites were brightly stained, just because of their thickness compared with the axon. (b) Tailless KIF5B·YFP were transfected into hippocampal neurons. Tailless KIF5B·YFP accumulated at the tips of axonal branches (arrows) but not dendrite tips. Cell body and proximal axon are indicated by arrowheads. (c) Tailless KIF17·YFP accumulated at the tips of dendrites (arrowheads) and axons (arrow). (d and e) Experiments on exchange of head domains revealed that head domains determine the destination of the tailless motors. MAP2 antibody is used as dendrite marker. (d) The KIF5 head and the KIF17 neck and rod constructs were destined for axons (green, arrows). The arrowhead indicates the cell body of transfected neuron. (e) The KIF17 head and the KIF5B head and the KIF17 neck and rod constructs were destined for the tips of dendrites (green). (f and g) Head exchange affects on polarized axonal transport. (f) Polarized axonal transport of VSV-G·GFP (green) was analyzed in the neurons that overexpress full-length KIF5B (red). VSV-G·GFP was preferentially sorted to the axon (arrow). (g) Preferential sorting of VSV-G·GFP (green, arrows) to the axon was inhibited in the neurons, which overexpress full-length KIF5 whose motor domain was replaced with KIF17 (red; see corresponding Videos 6 and 7). Fixation and immunocytochemistry to detect motor proteins was performed after live-cell imaging of VSV-G·GFP transport. (h and i) Head exchange does not affect on polarized dendrite sorting. NR2B·YFP distribution (green) was examined in the neurons, which overexpress authentic KIF17 (h, red) and full-length KIF5 whose motor domain was replaced with KIF5 (i, red). NR2B (green) was not sorted into axons in both cases. Arrows indicated the most likely candidates for axons. Bars, 10 μm. (j) Schematic diagram of the constructs. Head was exchanged at the border of head and neck-linker region of KIF5, and the corresponding region of KIF17 by the alignment. The colored amino acid sequences in the exchanged area were highly conserved. (k) Inhibition of polarized axonal transport by the head-exchanged KIF5. Bars indicate percentage of neurons with polarized B-APP·YFP transport. Data were collected from three independent cultures.
from the motor when they entered into axons, the cargoes will be excluded from the axon.

Next, we addressed the question whether KIF5 is activated preferentially between TGN and axons. To test it, motor proteins that can be recruited to MTs but cannot translocate along nor dissociate from MTs are suitable because such mutant motor proteins will show the site of initial recruitment of the motor proteins by their localization. We know of three such point mutations of kinesin (rigor kinesins) that are well characterized (Nakata and Hirokawa, 1995; Rice et al., 1999). We found that all the mutations (T92N, G234A, and E236A) show the same results in the case of KIF5B. KIF5 G234A mutant and corresponding G243 mutation distributed most intensely on MTs from the center of the cell body to the initial segment of axon (IS), whereas rigor-KIF2 did not. Bars, 10 μm. (g–i) Immuno-electron microscopy of rigor-KIF5 in hippocampal neurons. Rigor-KIF5 was labeled with 5-nm colloidal gold followed by silver enhancement. (g) Intense labeling of the IS is observable even at this low magnification (arrow). C indicates the cell body. (b) Higher magnification of the dendrite area in g (box D). (i) Higher magnification of axon area in g (box A). Note that extensive labeling of axons compared with dendrites. Bar, 500 nm.

KIF5::GFP to tubulin staining was 1.2 ± 0.4 [n = 14] in axons, and 0.5 ± 0.2 [n = 22] in dendrites. In contrast, rigor-KIF17 with corresponding G243 mutation distributed on MTs in both dendrites and the IS (Fig. 4 c). Double labeling with tubulin demonstrated high density association of the rigor-KIF17 with MTs in dendrites and the IS (Fig. 4 d). In the cell body, the rigor-KIF17 binds strongly to some MTs, but they show lower affinity with MTs in other areas of the cell body (fluorescence ratio of rigor-KIF17::YFP in axon to dendrites and dendrites to cell body were 109 ± 28.0% and 402 ± 281%, respectively [n = 25]). Simultaneous expression of rigor-KIF5 and rigor-KIF17 indicates that the preference of these two types is clearly different within the same neurons (Fig. 4 e). This distribution of rigor-KIF5 and -KIF17 is consistent with the destinations of tailless motors. Although motor domains of KIF5 and KIF17 had a property to bind to MTs in the IS, this is not always the case because rigor-KIF2 did not localize on MTs in the IS, as shown by the simultaneous expression of rigor-KIF2 and rigor-KIF5 in hippocampal neurons (Fig. 4 f). We further examined the axon preference of the rigor-KIF5 by using immunoelectron microscopy. Fig. 4 (g–i) shows biased binding of rigor-KIF5 to the IS (Fig. 4 g, arrow). These results suggest that KIF5 motor domain, as default, has a preference to the MTs in the IS and tailless KIF5 is preferentially sorted to axons.

Effects of low dose paclitaxel treatment

If the directional cue for the polarized axonal transport could be specifically blocked, we should expect that axonal
post-Golgi carriers, as well as tailless KIF5, be missorted to the tips of dendrites. We found that 1–10 nM paclitaxel, which inhibits MT dynamics (Derry et al., 1995) but does not inhibit the motor protein activity in vitro, drives both axonal vesicles and KIF5 to dendrites. In the presence of 10 nM paclitaxel, (1) tailless KIF5::YFP was accumulated at dendrite tips (Fig. 5 a); (2) rigor-KIF5::YFP failed to identify ISs (Fig. 5 b); and (3) axonal membrane proteins such as VSV-G::GFP tips (Fig. 5 a); (2) rigor-KIF5::YFP (green) was selected to dendrites in the presence of 10 nM paclitaxel. (c and d) VSV-G::GFP was initially observed 1 h after the temperature shift to 30°C from 19.5°C without paclitaxel (c), and 10 nM paclitaxel (d) was added to the medium. Axonal transport from the IS was unchanged. However, as a result of the decrease in the supply of vesicles from TGN, the amount of vesicles in the IS markedly decreased 1 h later (d, arrow). Note that dendrite staining is elevated in d. (e and f) β-APP::YFP was expressed overnight without (e) or with paclitaxel (f). (g and h) Kv2.1::YFP was expressed overnight without (g) or with paclitaxel (h). Kv2.1 (green) is a potassium channel sorted to the cell body and dendrites in the absence (g) and in the presence of paclitaxel (h). MAP2 staining (red) is superimposed on the KIF5 images in k and m (green). In control neurons, intense binding of KIF5 to the IS was observed (k and l, arrows), compared with other neurites. In contrast, when neurons were pretreated with 10 nM paclitaxel before permeabilization, binding of KIF5 to the axonal IS was similar to other neurites (m and n, arrows).

Figure 5. \textit{Paclitaxel at a low dose reverts the polarized sorting of axonal motor proteins as well as membrane proteins.} Data were obtained by CLSM with small pinhole and maximal Z-projection (b, k, l, m, and n) and with pinhole fully open (a, c, d, e, f, g, and h). Arrows indicate axons. MAP2 (red) was stained in a, b, e, l, and m. (a) Tailless KIF5::YFP (green) was selected to dendrites in the presence of 10 nM paclitaxel. (b) Rigor-KIF5::YFP (green) failed to accumulate in the IS in the presence of 10 nM paclitaxel. (c and d) VSV-G::GFP was initially observed 1 h after the temperature shift to 30°C from 19.5°C without paclitaxel (c), and 10 nM paclitaxel (d) was added to the medium. Axonal transport from the IS was unchanged. However, as a result of the decrease in the supply of vesicles from TGN, the amount of vesicles in the IS markedly decreased 1 h later (d, arrow). Note that dendrite staining is elevated in d. (e and f) β-APP::YFP was expressed overnight without (e) or with paclitaxel (f). (g and h) Kv2.1::YFP was expressed overnight without (g) or with paclitaxel (h). Kv2.1 (green) is a potassium channel sorted to the cell body and dendrites in the absence (g) and in the presence of paclitaxel (h). MAP2 staining (red) is superimposed on the KIF5 images in k and m (green). In control neurons, intense binding of KIF5 to the IS was observed (k and l, arrows), compared with other neurites. In contrast, when neurons were pretreated with 10 nM paclitaxel before permeabilization, binding of KIF5 to the axonal IS was similar to other neurites (m and n, arrows).
2.2 ± 0.8 in control \( [n = 21] \), and 1.0 ± 0.3 in the presence of paclitaxel \( [n = 20] \). In contrast, pretreatment of neurons with 10 nM paclitaxel inhibited the preferential axonal recruitment of KIF5 (Fig. 5, m and n).

MTs in the IS have distinct property from those in dendrites

Our paclitaxel experiments prompted us to see the MT dynamics around the cell body. For this purpose, we used EB1::YFP, which is known to bind to the growing tips of MTs (Tirnauer and Bierer, 2000). Although electron microscopists have long used the difference of MT organization in order to identify the IS around the cell body, their chemical property is not elucidated yet. Localization of conventional MAPs cannot explain this because, for example, although MAP2 and tau have been used as markers for dendrites and axons, MAP2 localizes in dendrites as well as in the IS, and the phosphorylated form of tau only localizes in the axons considerably distal to the IS. When we expressed EB1::YFP, in cultured hippocampal neurons, we found intense accumulation of EB1::YFP to the IS compared with the cell body and dendrites by CLSM at high Z-resolution (Fig. 6 a; see Fig. S5 a for wider field of view, available at http://www.jcb.org/cgi/content/full/jcb.200302175/DC1; fluorescence ratio of axon to dendrites was \( 172 ± 31.6\% \; [n = 20] \)). However, CLSM cannot visualize individual growing tips of MTs in the cell body. By using CAFM, we could visualize the growing tips of MTs as EB1 dots around the cell body. In a low level of EB1::YFP expression, we could observe the movement of individual EB1 dots in both axon ISs and dendrites (Fig. 6 b; Video 8, available at http://www.jcb.org/cgi/content/full/jcb.200302175/DC1). Number of EB1 dots per 10 \( \mu m^2 \) per 1 min by CAFM was \( 4.87 ± 2.23 \) in the ISs, \( 2.16 ± 1.59 \) in the dendrites, and \( 0.77 ± 0.13 \) in the cell body \( (n = 19) \), which was markedly reduced to \( 0.58 ± 0.08, 0.20 ± 0.18, 0.13 ± 0.06 \), respectively after a 10-min treatment of 10 nM paclitaxel. The inhibition of MTs dynamics by the paclitaxel also decreased the speed of EB1 dots from \( 4.6 ± 0.9 \; \mu m/\text{min} \) to \( 1.8 ± 1.1 \; \mu m/\text{min} \). We noticed that, in a higher level of EB1::YFP expression, MTs in the IS were fully decorated by EB1::YFP, whereas at the same time EB1::YFP labels only the tips of MTs as dots in the cell body and dendrites of the same neuron (Fig. 6 c, arrow; Video 9, available at http://www.jcb.org/cgi/content/full/jcb.200302175/DC1), which makes EB1::YFP an excellent marker for the axon around the cell body (Fig. 6, a and c). Control CAFM image of tubulin staining showed bright dendirtric staining (Fig. 6 d). Fig. S5 shows gallery of EB1 staining (Fig. S5 b) and immuno-electron microscopy of EB1::YFP in dendrites (Fig. S5 c) and axons (Fig. S5 d). Such spatial difference of EB1 behavior within a cell was never observed in nonneuronal cells at any level of EB1 expression. Our results demonstrate unique properties of MTs in the IS compared with those in the cell body and dendrites.

Discussion

We showed that axonal tubulovesicular organelles have kinesin-driven highly processive motility in the cell body and the majority of them moved directly to the axon (Figs. 1 and 2), consistent with the idea that there is a directional cue for polarized axonal transport. We demonstrated that KIF5 motor domain, as default, has preference to the MTs in the IS (Figs. 3 and 4). Low dose paclitaxel treatment specifically blocked the polarized axonal transport of both tailless motor and tubulovesicular organelles (Fig. 5). EB1 binding revealed there is a difference in the property of MTs between dendrites and axons just around the cell body (Fig. 6). Our results collectively suggest that the MT system provides a directional cue for the preferential axonal transport of KIF5 and tubulovesicular organelles.

Polarized transport of post-Golgi axonal carriers from the trans-Golgi network to the axons

Polarized distribution of membrane proteins may be achieved by the combination of a number of different mechanisms, which include: (1) sorting of membrane proteins to different post-Golgi carriers at TGN; (2) polarized transport of the carriers to different area of the cells; (3) selective fusion between the carriers and the plasma membranes; (4) endocytosis of missorted proteins and transcytosis; (5) selective stabilization or differential turnover of certain proteins in specific regions (Hirokawa et al., 1996); and (6) diffusion barrier at the plasma membrane (Winckler et al., 1999).
In this paper, we focused on the post-Golgi transport step in neurons because sorting at the transport step may play more important role in neurons than in epithelial cells, considering the characteristic structure of neurons. As for the axonal sorting in the transport step, three statuses should be discriminated: (1) carriers are randomly transported (no sorting); (2) carriers are preferentially transported to axons in a biased manner; and (3) carriers are exclusively inhibited to enter dendrites. We found that VSV-G::GFP carriers are preferentially transported to the IS in a biased manner (Figs. 1 and 2). Its incompleteness may be covered by the sorting mechanisms in subsequent fusion or endocytosis step (Jareb and Banker, 1998). Nevertheless, the rough sorting at the post-Golgi transport step is crucial when a large volume of axonal carriers is to be transported into narrow entry of axons at the cell body. Indeed, its specific inhibition by low dose paclitaxel caused a marked accumulation of axonal carriers at dendrite tips (Fig. 5).

As for dendrite sorting in the transport step, selective inhibition of transferrin receptor carriers to enter axons was shown (Burack et al., 2000). In the case of Kv2.1, small amount of carriers appear to enter the IS. However, its amount is far smaller than VSV-G::GFP (Fig. 2 f). As a result, total distribution of Kv2.1 was somatodendritic. Low amount is far smaller than VSV-G::GFP (Fig. 2 f). As a result, total distribution of Kv2.1 was somatodendritic. Low dose paclitaxel caused a marked accumulation of axonal carriers at dendrite tips (Fig. 5).

Directional cues for polarized axonal transport

Two possibilities are considered for directional cues for polarized axonal transport. One is a cytosolic diffusible signal; the other is the signal within the structural components. We observed that post-Golgi axonal carriers directly move from the TGN to the axon (Figs. 1 and 2). Our observation supports the latter possibility because the diffusible signals must always keep steep spatial difference within the cell body against their diffusion to accomplish the observed polarized axonal sorting. If diffusible signals were involved, we would observe that many axonal carriers move into the dendrites in the same side of the IS, whereas they scarcely move into the dendrites in the opposite side. This was not the case. Thus, the directional cues for the polarized axonal transport in mature neurons should be provided by structural components.

For the directional cues in the structural components, MTs and their associated proteins would play a main role because these carriers are transported on MTs by KIF5. One possible cue is MT organization itself. Difference in MT polarity has been used to explain the polarized axonal transport (Burack et al., 2000). However, in this hypothesis, axonal carriers should be initially transported from TGN to both axon and dendrites because polarity of MTs in dendrites are mixed. Thus, MT polarity cannot explain our present observation of VSV-G carriers, and here, we would like to refer to the possible interaction of MTs with the TGN at ultrastructural level. If axonal MTs are always associated with the Golgi complex/TGN exit sites, the budded axonal carrier may naturally transported to axons. MT dynamics may be necessary to capture the new Golgi complex exit sites. Tightly packed MTs in the IS may also contribute to the axonal transport because several MTs around a single carrier could interact with multiple motors on the axonal carrier to obtain high driving power for processive movements.

The other possible cue is the regulation of MT–motor head interaction. Indeed, we found preferential KIF5 binding to the MTs in the IS, which will contribute to the polarized axonal transport. Our data collectively suggest that this MT–KIF5 interaction may play an important role in the polarized axonal sorting. Although several studies suggest that
posttranslational modification of tubulin (Liao and Gundersen, 1998; Palazzo et al., 2003) affects MT–motor interaction, little attention was paid on the regulatory role of MT–motor interaction. Although MT–motor interaction might play a role in the pathway finding for the observed TGN to the axon transport, motor tail–cargo interactions might play a role in dendrite transport (Setou et al., 2002). How motor tail–cargo interaction regulates dendritic transport is an open question for future research.

Polarity of neuron has been extensively studied from two different aspects: one is structural components (cytoskeletal organization), and the other is the transport on the cytoskeleton (membrane trafficking). Our paper suggests close relationship between MT dynamics and polarized axonal transport. Given that MT cytoskeletons are organized as a result of its dynamics, polarized membrane sorting and polarized cytoskeletal organization) may obtain the polarity information from the same source, which will be important for these apparently two different phenomena to coordinately accomplish the polarity of neurons.

Materials and methods

Cell culture and transfection

Hippocampal cells were dissociated from the E16 mouse embryo and cultured after the method of Banker and Cowan (1977) with slight modification. Cells >10 culture days were used. Adenovirus infection was performed as described previously (Nakata et al., 1998) and a modified Ca-phosphate method was used for cDNA transfection (Kohrmann et al., 1999). Results are the same when the same constructs are introduced into hippocampal neurons by either method. Recombinant adenoviruses and mammalian expression vectors in the present paper is as follows: AdHSV-1::GFP, AdHSV-1::CFP, AdHSV-1::YFP, AdHSV-1::CFP::YFP, AdHSV-1::CFP::CFP, AdHSV-1::GFP, AdHSV-1::CFP::GFP, AdHSV-1::CFP::CFP, AdHSV-1::GFP::CFP, AdHSV-1::GFP::GFP, AdHSV-1::YFP::GFP, AdHSV-1::YFP::CFP, AdHSV-1::YFP::YFP, AdHSV-1::GFP::GFP, AdHSV-1::GFP::YFP, AdHSV-1::GFP::YFP, AdHSV-1::YFP::YFP.

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In vitro condonction

Tailless KIF5C fused with YFP tags in its COOH terminus was bacterially expressed at 18°C using pet21a vector, and His-tag purified. The hippocampal neurons were permeabilized with 10 μM paclitaxel in reconstitution buffer (0.1% Triton X-100, 100 mM Pipes, pH 6.9, 1 mM EGTA, 1 mM MgCl2, 1 mg/ml BSA) at 37°C for 10 min, then incubated with 0.05 mg/ml tailless KIF5C::YFP and 3 mg/ml purified tubulin in the reconstitution buffer without paclitaxel at room temperature for 20 min, fixed with ice-cold methanol, and stained with anti-MAP2 antibody.

Online supplemental material

Fig. S1 shows double labeling of tailless-motor proteins with axon and dendrite markers. Fig. S2 shows in vitro motility assay of KIF5/KIF17 chimera motor proteins. Fig. S3 shows that KIF5 G234A and KIF17 G243A mutants strongly bind to MTs. Fig. S4 shows MT organization of 100 nM paclitaxel-treated neurons at EM level. Fig. S5 shows EB1 accumulation in the IS by CLSM, CAFM, EM. Videos 1 and 2 show CLSM image of VSVG::GFP transport. Videos 3–5 show CAFM image of VSVG::GFP transport (Video 3) and Kv2.1::YFP (Vides 4 and 5). Videos 6 and 7 shows CLSM image of VSVG::GFP in neurons which overexpress full length KIF5C in the dendrite. Videos 8 and 9 shows CAFM image of the dynamics of EB1::YFP at low expression level (Video 8) and higher expression level (Video 9). Further comments on the data reported can be found in the online legends. Online supplemental material (Figs. S1–S5, Videos 1–9, and their legends) is available at http://www.jcb.org/cgi/content/full/jcb.200302175/DC1).

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