Kidins220/ARMS regulates Rac1-dependent neurite outgrowth by direct interaction with the RhoGEF Trio

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Summary
Neurite extension depends on extracellular signals that lead to changes in gene expression and rearrangement of the actin cytoskeleton. A factor that might orchestrate these signalling pathways with cytoskeletal elements is the integral membrane protein Kidins220/ARMS, a downstream target of neurotrophins. Here, we identified Trio, a RhoGEF for Rac1, RhoG and RhoA, which is involved in neurite outgrowth and axon guidance, as a binding partner of Kidins220. This interaction is direct and occurs between the N-terminus of Trio and the ankyrin repeats of Kidins220. Trio and Kidins220 colocalise at the tips of neurites in NGF-differentiated PC12 cells, where F-actin and Rac1 also accumulate. Expression of the ankyrin repeats of Kidins220 in PC12 cells inhibits NGF-dependent and Trio-induced neurite outgrowth. Similar results are seen in primary hippocampal neurons. Our data indicate that Kidins220 might localise Trio to specific membrane sites and regulate its activity, leading to Rac1 activation and neurite outgrowth.

Key words: Neuronal differentiation, Neurotrophin signalling, Kidins220/ARMS, Rac1, Trio

Introduction
During neuronal development, axons and dendrites have to navigate long distances to reach their physiological targets. This process includes extensive membrane remodelling and neurite elongation, which depend on extracellular signals that prompt changes in gene expression and cytoskeletal rearrangements at the growth cone. Amongst other extracellular inputs, neurotrophins have major roles in mediating neuronal differentiation, survival and death (Huber et al., 2003; Lu et al., 2005). Nerve growth factor (NGF), one of the best-characterised neurotrophins, signals through the neurotrophin receptors TrkA and p75NTR. Upon NGF binding, these receptors hetero-oligomerise and initiate pathways leading to sustained MAPK signalling, which is required for neurite outgrowth.

A molecule recently established to have a key role in sustained NGF-dependent MAPK signalling is Kidins220, also called ARMS (Arevalo et al., 2006; Arevalo et al., 2004; Hisata et al., 2007). Kidins220 is a highly conserved, integral membrane protein with large N- and C-terminal cytoplasmic domains (Iglesias et al., 2000; Kong et al., 2001). It acts as a downstream target of ephrin and neurophin receptors, such as p75NTR and TrkA (Arevalo et al., 2004; Kong et al., 2001), with which it forms a ternary complex (Chang et al., 2004). Overexpression of dominant-negative Kidins220 mutants (Arevalo et al., 2006; Bracale et al., 2007), or its downregulation by siRNA (Arevalo et al., 2004; Hisata et al., 2007) causes a strong inhibition of sustained MAPK signalling and neurite outgrowth in PC12 cells.

In addition to changes in gene expression, rearrangements of the actin cytoskeleton are essential for neurite elongation. Members of the small RhoGTPase family regulate this process, with Rac1, Cdc42 and RhoG supporting neurite extension and RhoA mediating growth-cone retraction (Dickson, 2001; Govek et al., 2005). RhoGTPases cycle between an active, GTP-bound form and an inactive, GDP-bound form. The activation is under the control of Rho guanine nucleotide-exchange factors (RhoGEFs) specific for a subset of RhoGTPases (Rossman et al., 2005), whereas they are switched off by their corresponding RhoGTPase-activating proteins (RhoGAPs).

Trio and its closely related family member Kalirin are recent additions to the growing family of RhoGEFs involved in neurite outgrowth. Both Trio and Kalirin possess two independent RhoGEF domains: the first (GEF1) is specific for Rac1 and RhoG, and the second (GEF2) is specific for RhoA (Bateman and Van Vactor, 2001; Bellanger et al., 1998; Blangy et al., 2000; Debant et al., 1996; Penzes et al., 2001). Trio has been implicated in axon guidance in a variety of organisms, such as Caenorhabditis elegans, Drosophila melanogaster and Mus musculus, via its first GEF domain (Awasaki et al., 2000; Bateman et al., 2000; Braincon-Marjollet et al., 2008; Liebl et al., 2000; Lin and Greenberg, 2000; Newsome et al., 2000; Steven et al., 1998). Trio-knockout mice die between embryonic day (E) 15.5 and birth (O’Brien et al., 2000). They display skeletal muscle deformity, aberrant cellular organisations in the brain (O’Brien et al., 2000) and axonal guidance defects, which relates to the involvement of Trio in netrin-1/DCC signalling (Braincon-Marjollet et al., 2008). Further studies show that Trio also regulates the organisation of neuronal clusters in the hindbrain in vivo (Backer et al., 2007).

In PC12 cells Trio is the rate-limiting factor of NGF-induced neurite outgrowth by the activation of RhoG via GEF1 (Estrach et al., 2002). This process is regulated by the N-terminal spectrin domains of Trio and its first SH3 domain (Estrach et al., 2002). Whereas the effect of the GEF1 of Trio on neurite outgrowth is easy to rationalise, the inhibition of NGF-induced neurite outgrowth observed by expressing the spectrin repeats and the first SH3 domain is still lacking a precise explanation.

To date, the mechanisms implicated in neurotrophin signalling down to the re-organisation of the actin cytoskeleton are only partially understood. Therefore, factors capable of receiving and integrating extracellular signals, and at the same time, modulating the actin
cytoskeleton, could have a key role in orchestrating signalling events and actin rearrangements that lead to neurite outgrowth. Kidins220 is ideally placed to fulfil this function by acting as a scaffolding protein for neurotrophin receptors (Arevalo et al., 2004; Kong et al., 2001) and providing docking sites for modulators of the actin cytoskeleton. Here, we show that the N-terminal ankyrin repeats of Kidins220 bind directly to the spectrin domains of the RhoGEF Trio. Overexpression of the ankyrin-rich domain of Kidins220 leads to enhanced Rac1 activation and to impairment of Trio- and NGF-induced neurite elongation. Altogether, these data suggest that the interaction between Trio and Kidins220 has an important role in neurite outgrowth in PC12 cells and primary neurons.

Results

Interaction between Kidins220 and Trio

To explore the role of Kidins220 in neurite elongation, we searched for possible interacting partners by a yeast two-hybrid approach using the N-terminal domain of Kidins220 as bait. This intracellular domain consists of 11 ankyrin repeats (1-402 aa) (Fig. 1A), but does not include the Walker A motif (467-474 aa), which, together with the Walker B (771-775 aa), forms a P-loop NTPase domain. The N-terminal 672 residues of the RhoGEF Trio, which contains the Sec14 and its first four spectrin domains (Fig. 1B), were among the positive hits (for a complete list of putative interactors, see supplementary material Table S1). This interaction was tested by re-transforming yeast, either with the N-terminal domain of Kidins220 (1-402 aa; Kidins2201-1402), or with its C-terminus (1209-1762 aa; Kidins2201209-1762) together with Trio1-472. Only yeast co-transformed with the ankyrin repeats of Kidins220 and the N-terminus of Trio showed robust growth (supplementary material Fig. S1A), hence confirming the result of the yeast two-hybrid screen.

Next, we verified the interaction of Kidins220 with Trio by co-immunoprecipitation experiments of endogenous proteins in PC12 cells. Anti-Trio (Fig. 1C) and anti-Kidins220 antibodies (Fig. 1D) were able to specifically co-immunoprecipitate Kidins220 and Trio, respectively. This interaction took place both in the absence and in the presence of NGF (Fig. 1E), suggesting that the interaction between Trio and Kidins220 is largely constitutive, as was previously observed for possible interacting partners by a yeast two-hybrid screen. The efficiency of the Trio-Kidins220 co-immunoprecipitation was comparable with other known interactors of Kidins220, such as p75NTR (Chang et al., 2004) or kinesin-1 (Brajcic et al., 2007).

Because of the high sequence similarity between Trio and its closely related family member Kalirin, we decided to test whether Kidins220 also interacted with Kalirin. Although we did not detect an interaction between endogenous Kidins220 and Kalirin, Kalirin9 weakly co-immunoprecipitated with Kidins220 in PC12 cells transfected with HA-tagged Kidins220 (Fig. 1F). Interestingly this Kalirin isoform was previously shown to interact with p75NTR and activate RhoA (Harrington et al., 2008). However, since we found Trio in the yeast two-hybrid screen and we were able to co-immunoprecipitate both endogenous Trio and Kidins220, we focussed our investigation on this specific interaction.

To map the determinants of the interaction of Trio with Kidins220, co-immunoprecipitation experiments were performed with the indicated GFP-tagged Trio constructs (Fig. 1B,G). PC12 cells were transfected, treated with NGF for 24 hours and extracts were immunoprecipitated with anti-Kidins220 antibodies. As shown in Fig. 1G, the fragment containing the spectrin repeats of Trio (Trio1-1203) was immunoprecipitated, whereas the other domains of Trio, including the large C-terminus (Trio1813-3038), were not. This association was specific, because it was not detected when this lysate was incubated with a rabbit pre-immune serum (pre-I) used as negative control. Because the band of GFP-tagged Trio1579-1816 ran at a similar molecular mass to the immunoglobulin heavy chain, anti-Kidins220 antibodies and pre-immune serum coupled to protein-G-Sepharose were loaded on the same gel (Fig. 1G and supplementary material Fig. S1B). Comparison of these lanes showed that the contaminating bands, indicated by black and grey arrowheads, had slightly different mobility than GFP-tagged Trio1579-1816.

To test whether the interaction between Kidins220 and Trio was direct, the His6-tagged N-terminal ankyrin-rich domain of Kidins220 was expressed and purified. This fragment was subsequently incubated with either GST alone or the GST-tagged Sec14 domain of Trio1-232, spectrin domains I-4 (Trio255-699) and 5-8 (Trio696-1203) (supplementary material Fig. S1C). Both spectrin clusters, and to a lesser extent the Sec14 domain, bound to Kidins2201-402 (Fig. 1H), indicating that this interaction is direct and that the N-terminus of Trio, including all spectrin domains, participates in the formation of the Trio-Kidins220 complex.

Kidins220 and Trio colocalise at neurite tips

The binding of Kidins220 to Trio suggests that Kidins220 affects actin cytoskeleton dynamics. If this were the case, Kidins220 should localise, at least in part, to regions enriched in actin microfilaments. To test this hypothesis, PC12 cells were differentiated for 3 days with NGF, then fixed and stained for F-actin using fluorescently labelled phalloidin, and for endogenous Kidins220. As shown in Fig. 2A,B, F-actin and Kidins220 showed an extensive overlap at neurite tips (arrows). This enrichment of Kidins220 at neurite tips was not due to an accumulation of plasma membrane or cytoplasm at these sites, because Kidins220 and a membrane-bound version of mRFP (mRFP-CAAX; Fig. 2C) or soluble GFP (Fig. 2D) did not show the same cellular distribution (arrowheads). Interestingly, Trio also localises to actin-rich regions at growth cones (Estrach et al., 2002), a finding that prompted us to directly compare the localisation of Trio and Kidins220. Because anti-Trio antibodies do not recognise the endogenous protein in immunofluorescence, GFP-tagged full length Trio was expressed in NGF-differentiated PC12 cells, which were then immunostained for Kidins220. Both proteins could be detected at the tip of neurites (Fig. 2E,F), indicating that the interaction between Trio and Kidins220 takes place on extending neurites and growth cones.

What is the molecular function of the Kidins220-Trio complex? Since Kidins220 is an integral membrane protein and interacts directly with Trio, it might drive the recruitment of the latter, to mainly cytosolic protein, to specific membrane domains. To test this hypothesis, we overexpressed HA-tagged Kidins220 in PC12 cells and tested whether the cellular localisation of Trio is influenced by full-length Kidins220. Owing to the absence of suitable anti-Trio antibodies for immunofluorescence (see above) and the very low transfection efficiency of full-length Trio, we used a truncated Trio construct containing all spectrin repeats, the first GEF and SH3 domain (Fig. 1B). This Trio fragment (Trio1-1813) was shown to mimic full-length Trio in promotion of NGF-induced neurite outgrowth in PC12 cells (Estrach et al., 2002). Since GFP-tagged Trio1-1813 is partially cytoplasmic as judged by immunofluorescence (Fig. 3A), co-expression of this fragment with full-length Kidins220...
Kidins220/ARMS binds Trio

Fig. 1. Interaction between Kidins220 and Trio. (A) Kidins220 is an integral membrane protein containing four transmembrane domains (TMs) and large N- and C-termini exposed to the cytoplasm. At the N-terminus, primary sequence analysis predicts 11 ankyrin repeats (1-402 aa) and a Walker A motif (467-474 aa), which together with the Walker B motif (771-775 aa) forms a P-loop NTPase domain. The C-terminus contains a proline-rich domain, a sterile alpha motif (SAM)-like domain and a PDZ-binding motif. Kidins220 binds kinesin light chain via the kinesin-1-interacting motif (KIM). Several phosphorylation sites are also present (not shown). The Kidins220 fragments used in this study are underlined. (B) Trio is a 348 kDa protein, comprised of a putative Sec14-like domain, followed by eight spectrin repeats (255-1203 aa), two Rho-GEF and SH3 domains, an immunoglobulin (Ig)-like domain and a kinase domain at the C-terminus. The Trio fragments used in this study are underlined. (C,D) The interaction between Kidins220 and Trio was confirmed by co-immunoprecipitation of both endogenous proteins. NGF-treated PC12 cell extracts were immunoprecipitated with anti-Trio (C) or anti-Kidins220 antibodies (D). Western blots were probed with anti-Kidins220 and anti-Trio antibodies, respectively. In both experiments, endogenous Kidins220 and Trio were recovered in the pellet. (E) The association of Trio and Kidins220 is not modulated by NGF. To test whether the Kidins220-Trio interaction was NGF-dependent, PC12 E2 cells – a PC12 cell clone with enhanced sensitivity to neurite outgrowth promoting factors (Estrach et al., 2002; Wu and Bradshaw, 1995) – were incubated either with or without NGF for 24 hours, lysed and then immunoprecipitated with anti-Trio antibodies. (F) PC12 cells were transfected with HA-Kidins220 and HA-ULK1 as negative control, and then immunoprecipitated with anti-HA antibodies. The western blot was probed with anti-Kalirin antibodies, which revealed a weak band of Kalirin9 in the Kidins220 lane, but not in control immunoprecipitations. (G) To map the binding domains of Trio, PC12 cells were transfected with GFP-Trio constructs and lysates were immunoprecipitated with anti-Kidins220 antibodies. Immunoglobulin-contaminating bands of the anti-Kidins220 antibodies and of the pre-immune serum (Pre-I) are indicated with black and grey arrowheads, respectively. Only the spectrin domains of Trio (Trio1-1203) are immunoprecipitated by Kidins220 antibodies. (H) The ankyrin repeats of Kidins220 and the N-terminal fragments of Trio (Trio1-232, Trio255-699, Trio696-1203) were expressed as recombinant proteins and tested for direct binding. The ankyrin repeats (Kidins2201-402) bind to a small extent to the Sec14 domain (Trio1-1203), but interact equally well with the first (Trio255-699; repeats 1-4) and the second half of the spectrin domains (Trio696-1203; repeats 5-8). SN, supernatant; B, beads.
determined its recruitment onto Kidins220-positive membrane-bound puncta (double-positive structures = 50.3±7.4%) (Fig. 3B,C; arrows). This effect was not observed in cells co-expressing full-length Kidins220 and GFP (double-positive structures = 5.3±1.2%) (Fig. 3D, arrowheads). In contrast to full-length Kidins220, expression of the membrane-anchored Kidins220403-1762, which lacks the Trio-binding domain, was not able to localise Trio 1-1813 to the membrane (double-positive structures = 8.7±3.3%) (Fig. 3E,F; arrowheads), indicating that full-length Kidins220 might help to localise Trio to specific membrane domains and as a consequence, regulate its cellular activities.

Kidins220$^{1-402}$ activates Rac1 but not RhoG

To investigate the functional effects of a Trio-Kidins220 complex, we tested whether Kidins220 would activate downstream effectors of Trio. Since NGF-induced neurite outgrowth is mediated by its first GEF domain (Estrach et al., 2002), we looked at the activation of Rac1 and RhoG, both of which can be activated by this domain. Full-length Kidins220, the Trio-interacting ankyrin repeats (Kidins220$^{1-402}$) and the remaining C-terminal portion of Kidins220 (Kidins220$^{403-1762}$) were expressed as HA-tagged proteins in HEK293 cells (see Materials and Methods and supplementary material Fig. S2A). Cell lysates were then examined for the amount
of activated, GTP-bound Rac1 using a GST-pull-down assay performed with the Cdc42/Rac1 interacting-binding (CRIB) domain of the Rac1 effector protein Pak1. Overexpression of Kidins220-403, and to a small but significant extent of full-length Kidins220, led to a reproducible activation of Rac1 (Fig. 4A, B), suggesting a possible regulation of the TrioGEF1 activity by Kidins220.

However, these experiments did not address whether the Rac1 activation by the Kidins220-Trio complex was direct or was due to the activation of RhoG, which in turn could activate Rac1 via the DOCK180-ELMO complex (Katoh and Negishi, 2003). To test this, we performed a RhoG activation assay with the GST-tagged kinectin domain 1 (KID1) of the RhoG effector kinase (Vignal et al., 2001), following a protocol similar to that described above for the Rac1 activation. For the detection of endogenous RhoG, we used a monoclonal anti-RhoG antibody, which does not crossreact with Rac1 (Meller et al., 2008). HEK293 cells were transfected with HA-tagged Kidins220 constructs, with GFP as negative and TrioGEF1 as positive controls (supplementary material Fig. S2C). As expected, TrioGEF1 potently activated endogenous

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**Fig. 3. Trio associates with Kidins220-positive membrane structures.** (A, B) PC12 cells were transfected with GFP-tagged Trio1-1813 and HA-tagged full length Kidins220, differentiated for 3 days with NGF, fixed and analysed by immunofluorescence. GFP-tagged Trio1-1813 is partially diffused (A), but it is recruited to Kidins220-positive puncta upon co-expression with full-length Kidins220 (B, arrows). (C) A high-magnification view of the neurite tip in B. Arrows indicate colocalising puncta. The transfected cell and the growth cone are outlined for better visibility. (D) Co-expression of GFP and HA-tagged full-length Kidins220 did not result in a recruitment of GFP to Kidins220-positive puncta (arrowheads). (E) PC12 cells were co-transfected with GFP-tagged Trio1-1813 and HA-tagged Kidins220-403-1762 and treated as in B. GFP-tagged Trio1-1813 does not associate with Kidins220-403-1762-positive structures (arrowheads). (F) An enlargement of the neurite tip in E. FL, full length. Scale bars: 5μm.
Kidins220 expression activates Rac1 but not RhoG. (A) HEK293 cells were transfected with the indicated constructs and subjected to a Rac1 activation assay. Cells transfected with Kidins2201-402 and to a lesser extent with full-length Kidins220 show an increase in Rac1-GTP levels. (B) Quantification of three independent experiments. Rac1-GTP levels were expressed in arbitrary units (AU), after they had been normalised to the expression of each construct and to the total Rac1 content. The activation of Rac1 by Kidins2201-402 and full-length protein is significant in the Student’s t-test; *P<0.05; **P<0.01. Error bars represent s.e.m. (C) HEK293 cells were transfected with the indicated constructs and subjected to a RhoG-activation assay. The first GEF domain of Trio activated endogenous RhoG, but none of the other constructs did. (D) The means of three independent experiments. Error bars represent s.e.m. FL, full length; **P<0.01. (E) PC12 cells were differentiated for 3 days with NGF, then fixed and stained for endogenous Kidins220 (green) and Rac1 (red). Arrows indicate overlapping puncta and arrowheads show nonoverlapping areas. (F) Trio-GFP was expressed in NGF-differentiated PC12 cells, which were subsequently fixed and immunostained for endogenous Kidins220 (blue) and Rac1 (red). (G) Positive structures for all three proteins are observed at neurite tips (white, arrows), whereas soluble GFP is distributed rather uniformly throughout the cell. The arrowhead indicates a Kidins220/Rac1-positive structure, which was not enriched in GFP. Scale bars: 5 μm.
However, Kidins220 and Rac1 did not colocalise on all neurite protrusions (Fig. 4E, arrowheads), reflecting the possibility that not all neurites undergo dynamic changes at any given time, and some of them might even undergo retraction. Consistently, Rac1 is transiently activated at the cell periphery and neurite tips of NGF-differentiated PC12 cells, and this event is required for neurite outgrowth (Aoki et al., 2004). Next, we transfected GFP-tagged Trio in PC12 cells, and after 3 days of differentiation with NGF, the localisation of endogenous Rac1 and Kidins220 was revealed by immunostaining. As shown in Fig. 4F, the three proteins colocalised at some neurite tips: sites where they might actively promote neurite extension. This localisation is specific for Trio-GFP, because GFP was not enriched at these sites (Fig. 4G, arrowhead).

The ankyrin repeats of Kidins220 inhibit NGF-induced neurite outgrowth

Given the importance of Rac1 and Trio in neurite outgrowth, we wondered whether overexpression of Kidins220 and its fragments would affect this process. We decided to pursue this strategy, instead of Kidins220 downregulation by RNA interference, since the latter approach, which has been previously shown to inhibit neurite outgrowth in PC12 cells (Hisata et al., 2007), would only provide insights on the overall function of Kidins220, and would not allow us to distinguish between the role of its interaction with Trio or with other binding partners (Arevalo et al., 2006; Arevalo et al., 2004; Bracale et al., 2007; Hisata et al., 2007; Iglesias et al., 2000; Kong et al., 2001; Luo et al., 2005). Therefore, we analysed the extent of NGF-induced differentiation in PC12 cells after overexpression of Kidins2201-402, Kidins220403-1762 and the full-length protein, whilst GFP was used as a negative control (Fig. S3A). Cells were treated for 3 days with NGF, fixed, and the length protein, whilst GFP was used as a negative control (Fig. 5A) is not due to massive effect on neurite outgrowth (20.7±2.2% differentiated cells versus 69±6.9% for GFP-transfected cells; Fig. 5A) is not due to massive effect on neurite outgrowth (20.7±2.2% differentiated cells versus 69±6.9% for GFP-transfected cells; Fig. 5A). Neurite outgrowth was quantified by counting cells bearing neurites at least twice as long as their cell body.

Quantification was obtained from three independent experiments (± s.e.m.). At least 62 cells were analysed per condition. FL, full length. **P<0.01. (B) PC12 cells were co-transfected with the Raichu Rac1/Rac1-CT and HA-tagged Kidins2201-402 (upper panel) or Kidins220403-1762 (lower panel). The FRET ratio is shown in intensity-modulated display (IMD) format, ranging from a FRET ratio 0 to 2.5. High FRET ratios are observed inside the cell after co-transfection of Kidins220403-1762 (lower panel). Scale bars: 10 μm. (C) For quantification, the cell area (in % of the whole cell) occupied by a FRET ratio of 2.4 and above was summed (see the Materials and Methods for details). These values were then compared between cells co-expressing the Raichu construct with Kidins2201-402 (red circles) or Kidins220403-1762 (blue squares). Each symbol represents an individual cell. The red and blue bars indicate the mean of 49 Kidins2201-402-Raichu Rac1/Rac1-CT co-transfected cells or 42 Kidins220403-1762-Raichu Rac1/Rac1-CT co-transfected cells, respectively. Cells expressing Kidins2201-402 exhibit more cell area occupied by high FRET ratios. *P<0.05.

Based on these results, we wondered how overexpression of Kidins2201-402, which was able to drive Rac1 activation (Fig. 4A), could at the same time inhibit neurite outgrowth. As seen by immunofluorescence, the ankyrin repeats were distributed evenly throughout the cell (supplementary material Fig. S3A, inset). Therefore, an attractive possibility is that Rac1 activation by Kidins2201-402 occurs ubiquitously in transfected cells, instead of at specific sites on the plasma membrane, which is a prerequisite for neurite formation (Aoki et al., 2004; da Silva and Dotti, 2002). In this light, Kidins2201-402 overexpression would mimic the inhibitory effect on NGF-dependent neurite outgrowth induced by overexpression of a constitutively active Rac1 mutant (Aoki et al., 2004). To test this hypothesis, we used the Raichu construct Rac1/Rac1-C-terminus (CT) as a biosensor to monitor Rac1 activation in live cells. This probe monitors the balance of activity between GEFs and GAPs acting on Rac1 and was previously used to study the localisation of activated Rac1 in NGF-treated PC12 cells (Aoki et al., 2004). We co-transfected this biosensor with HA-tagged Kidins2201-402 or Kidins220403-1762 in PC12 cells and examined the localisation of activated Rac1. To this end, the FRET ratio between the emission intensities of acceptor and donor was measured in living cells. In cells co-transfected with Kidins2201-402 we observed activation of Rac1 throughout the cell (Fig. 5B, upper panel). By contrast, cells co-transfected with the C-terminus of Kidins220, which we used as a negative control, showed lower levels of GTP-bound Rac1 that partially localised along the plasma membrane (Fig. 5B, lower panel, arrows). Aoki and colleagues devised an elegant way of measuring cell areas with a FRET ratio above a certain threshold, which allows testing of whether a localised activation of Rac1 is required for neurite outgrowth (Aoki et al., 2004). They could use as a reference the same cell before NGF treatment, whereas in our experiments, which involve two cell populations transfected with different constructs, we had to empirically set a threshold ratio above which we could detect a difference in Rac1 activation (see the Materials and Methods). We observed a significant difference in...
the cell area occupied by activated Rac1 in cells cotransfected with Kidins2201-402 or Kidins220403-1762 at a FRET ratio above 2.4 (Fig. 5C). This result correlates well with our biochemical data (Fig. 4A,B). Cells transfected only with Raichu Rac1/Rac1-CT displayed an intermediate value (data not shown). At present we are unable to assess whether this difference is due to an inhibitory effect of the C-terminus of Kidins220, or whether the transfection of the Raichu construct alone results in a higher basal activation of Rac1.

Taken together, these results suggest that the ankyrin repeats of Kidins220 triggered a ubiquitous activation of Rac1. Since a localised activation of Rac1 at specific sites at or close to the plasma membrane is necessary for neurite extension, overexpression of Kidins2201-402 determined a net inhibition in NGF-induced neurite outgrowth (Fig. 5A).

Effect of Kidins220 on Trio- and RhoG-induced neurite elongation
To study more specifically the functional consequences of the interaction between Kidins220 and Trio, we looked at the effect that Kidins220 and its deletion mutants might have on Trio-induced neurite outgrowth. To this end, PC12 E2 cells, a PC12 cell clone with enhanced sensitivity to factors promoting neurite outgrowth (Estrach et al., 2002; Wu and Bradshaw, 1995), were double-transfected with GFP-Trio1-1813 and either mRFP, full-length Kidins220 or its deletion mutants. As in Fig. 3, we used the C-terminal truncated version of Trio (Trio1-1813). After transfection, cells were incubated for 48 hours in full growth medium, then fixed and analysed for their neurite length, which were considered to be positive (n=3 independent experiments). PC12 E2 cells were co-transfected either with GFP-tagged Trio1-1813 (C) or RhoG (E) and the indicated HA-tagged Kidins220 deletion mutants or mRFP and mRFP-CAAX as negative controls. After 48 hours, double-transfected cells were quantified for neurite outgrowth in three independent experiments, as previously described. Kidins2201-402 and the membrane-bound Kidins2201-402-CAAX blocked Trio-induced neurite elongation (C, D), whereas full-length Kidins220 enhanced RhoG-induced neurite outgrowth (E). Error bars represent s.e.m. At least 154 cells were analysed for each construct. FL, full length; **P<0.01.

Fig. 6. Quantification of Trio and RhoG-induced neurite outgrowth. (A,B) PC12 E2 cells were transfected with mRFP, mRFP-CAAX or HA-tagged Kidins220 deletion mutants. After 48 hours expression in full growth medium, cells were fixed and examined for neurite outgrowth. Cells, which bore one neurite at least double the size of the diameter of its cell body, were considered to be positive (n=3 independent experiments). PC12 E2 cells were co-transfected either with GFP-tagged Trio1-1813 (C) or RhoG (E) and the indicated HA-tagged Kidins220 deletion mutants or mRFP and mRFP-CAAX as negative controls. After 48 hours, double-transfected cells were quantified for neurite outgrowth in three independent experiments, as previously described. Kidins2201-402 and the membrane-bound Kidins2201-402-CAAX blocked Trio-induced neurite elongation (C, D), whereas full-length Kidins220 enhanced RhoG-induced neurite outgrowth (E). Error bars represent s.e.m. At least 154 cells were analysed for each construct. FL, full length; **P<0.01. (F) HEK293 cells were transfected with HA-tagged Kidins2201-402, Kidins220403-1762, mRFP or mRFP-CAAX and subjected to a membrane-cytosol fractionation. Syntaxin6 was used as a membrane marker and SOD1 as a marker for the cytosol. Whereas the ankyrin repeats are partially cytosolic, Kidins2201-402-CAAX and mRFP-CAAX associate with membrane fractions.
Fig. 7C,D). However, neurons overexpressing Kidins2201-402 were not necrotic (Fig. 7Bb, green) or apoptotic. Therefore we performed a co-staining with propidium iodide (green) or antibodies against activated caspase 3 (red) (panels b). Scale bars: 10 μm. (D) The average of four independent experiments. Neurons transfected with Kidins2201-402 display impaired neurite outgrowth compared with control cells. Error bars represent s.e.m. At least 227 neurons were analysed for each construct. *P<0.05; n.s., not significant.

The N-terminus of Kidins220 inhibits neurite outgrowth in primary neurons
To confirm the role of the Trio-Kidins220 interaction in neurite elongation, we tested the effect of Kidins2201-402 in primary neurons. For this experiment, we chose hippocampal neurons, because Trio-knockout mice displayed abnormal neural organisation in the hippocampus (O’Brien et al., 2000) and Kidins220 is highly expressed in this region of the brain (Kong et al., 2001; Wu et al., 2009). Therefore E18 hippocampal neurons were nucleofected with Kidins220 deletion mutants or GFP (as a negative control). After 1 day in vitro, neurons were fixed and neurite length was measured (Fig. 7A-C). Under these conditions, GFP-expressing hippocampal neurons had a normal appearance, with the majority of cells showing one or more neurites (Fig. 7A,D). Neurons expressing Kidins2201-402 also showed neurites at this stage (Fig. 7C,D). However, neurons overexpressing Kidins2201-402 were not able to develop neurites (Fig. 7B,D). Because of their rounded appearance, we were concerned that these cells might be necrotic or apoptotic. Therefore we performed a co-staining with propidium iodide, which labels the nucleus of necrotic cells when added before fixation. In addition, nucleofected neurons were treated with an antibody specific for the activated form of caspase 3, an early apoptosis marker. These tests revealed that neurons expressing Kidins2201-402 were not necrotic (Fig. 7Bb, green) or apoptotic (Fig. 7Bb, red). Unfortunately, we were not able to express full-length Kidins220 in neurons, because of its propensity to aggregate upon overexpression. Since most hippocampal neurons expressing Kidins2201-402 did not bear neurites after 1 day in vitro, it is likely that the ankyrin repeats affects neurite initiation, which is important for both dendritic and axonal growth. This is in accordance with previous studies, which showed that Kidins220 regulates dendritic branching in vivo (Wu et al., 2009), and modulated the development of both axons and dendrites (Higuero et al., 2009).

Discussion
We analysed the interaction of the scaffolding molecule Kidins220 with the RhoGEF Trio and ascertained its functional consequences. Mapping of the interaction sites between these two proteins revealed that the N-terminal ankyrin-rich domain of Kidins220 (Kidins2201-402) bound directly to the N-terminal spectrin repeats of Trio. Both proteins colocalised at the tips of neurites in NGF-differentiated PC12 cells, where F-actin and Rac1 also accumulated. Rac1, but not RhoG, was specifically activated by Kidins2201-402 and, to a small extent, by the full-length protein. Strikingly, overexpression of the ankyrin repeats of Kidins220 inhibited neurite outgrowth, whereas its C-terminus had no effect.

Because expression of Kidins2201-402 specifically inhibited both NGF- and Trio-induced neurite outgrowth, and NGF-mediated outgrowth depends on Trio (Estrach et al., 2002), it is likely that the dominant-negative effect elicited by Kidins2201-402 is due to its interaction with the spectrin-rich domain of Trio. Our results might therefore explain the observed inhibitory effect of the latter domain
on NGF-dependent differentiation (Estrach et al., 2002). The inhibition of neurite outgrowth by Kidins220(1-402) is not a general effect, because its overexpression did not affect neurite extension induced by RhoG (Fig. 6E). This is in agreement with our biochemical data that Kidins220 did not activate RhoG. However, full-length Kidins220 increased RhoG-induced neurite outgrowth (Fig. 6E). Because both RhoG and Kidins220 can activate Rac1 independently (Fig. 8A; pathway A and B), contributions from these two signalling cascades could occur in parallel, and thus their effects on neurite outgrowth might be additive. By contrast, full-length Kidins220 was not able to synergise with Trio in promoting neurite elongation (Fig. 6C), suggesting that they act on the same pathway (Fig. 8A; pathway B), with Trio being rate-limiting.

We observed a selective activation of Rac1, but not of RhoG, by the ankyrin repeats of Kidins220. Given the direct interaction between Kidins220 and Trio that we report here, we propose that the activation of Rac1 is mediated by Trio. This selectivity for Rac1 is not unprecedented. In fact, DCC/Netrin-induced neurite outgrowth mainly uses the Trio-dependent Rac1 pathway and a dominant-negative form of RhoG did not interfere with this process (Briancon-Marjollet et al., 2008). In addition, Backer and colleagues reported that Trio controls the organisation of neuronal clusters in the hindbrain via Rac1 and not RhoG (Backer et al., 2007), although previous reports show that Rac1 can be activated by RhoG via the DOCK180-ELMO complex (Katoh and Negishi, 2003). Since the TrioGEF1 domain is able to activate both RhoG and Rac1 (Bellanger et al., 1998; Blangy et al., 2000; Chhatriwala et al., 2007), one attractive possibility is that it is the specific process that determines whether RhoG or Rac1 is activated. It was previously reported that RhoG, but not Rac1, mediates the membrane association of Trio, since Trio alone was not able to do so (Skowronek et al., 2004). In our system, Trio might be recruited to the membrane with the help of Kidins220 (Fig. 8A), because Kidins220 is an integral membrane protein and its binding to Trio must occur at specific membrane sites. In this scenario, Rac1 could be activated by Trio without an activation of RhoG and its downstream targets, such as Cdc42 (Gauthier-Rouviere et al., 1998).

The finding that the expression of Kidins220(1-402) activated Rac1 and inhibited neurite outgrowth phenocopies the effects of expressing constitutively-active Rac1, which also leads to a reduction of neurite outgrowth in PC12 cells (Aoki et al., 2004). A possible explanation for this phenomenon is that Rac1 needs to be activated at specific sites, such as neurite tips, to sustain neurite extension (Aoki et al., 2004). However, Kidins220(1-402) is not localised at these sites, allowing a ubiquitous activation of Rac1 (Fig. 5B) and consequently a block of differentiation (Fig. 8B, left). Full-length Kidins220, which also activated Rac1 although to a very small extent, did not prevent neurite elongation, most likely because it is correctly localised to neurite tips similarly to endogenous Kidins220 (Fig. 8B, right).

The phenotypic differences observed by expressing full-length Kidins220 and its ankyrin-rich domain do not only originate from their different cellular localisation, but might also derive from the fact that Kidins220 consists of two functionally distinct N- and C-terminal domains (see Fig. 1A), whose crosstalk is probably essential to exert its function as a scaffolding protein (Fig. 8B; right). In contrast to the full-length protein, Kidins220(1-402) is unable to receive any information from the C-terminal portion of Kidins220, which is known to have a key role in the binding of neurotrophin receptors and contains several protein-protein interaction domains (Fig. 1A) (Arevalo et al., 2006; Arevalo et al., 2004; Bracale et al., 2007; Hisata et al., 2007; Iglesias et al., 2000; Kong et al., 2001; Luo et al., 2005). Crucially, the C-terminal domain undergoes tyrosine phosphorylation upon neurotrophin stimulation, and this event is required for the recruitment of downstream effectors necessary for sustained MAPK signalling (Arevalo et al., 2006) (pathway C in Fig. 8A).

Kidins220 might also exert its function through other Trio-related proteins. This view is supported by preliminary data showing that the inhibition of neurite outgrowth mediated by Kidins220(1-402) overexpression is still observed in neurons derived from Trio-knockout mice (data not shown) (O’Brien et al., 2000), and by the interaction between Kidins220 and Kalirin, a Trio family member. Altogether, these results suggest that the functions of Trio and Kalirin might overlap. This is not surprising, since in C. elegans only one member of the Trio/Kalirin family, called Unc-73, is expressed (Bateman and van Vactor, 2001), suggesting that multiple
roles for Trio and Kalirin were acquired with the increased complexity of the organisms. Interestingly, Kidins220 interacts with the TrkB receptor and is phosphorylated upon treatment with its ligand, brain-derived neurotrophic factor (BDNF) (Arevalo et al., 2004; Kong et al., 2001; Luo et al., 2005). In addition, Kidins220 is a downstream target of ephrins (Kong et al., 2001; Luo et al., 2005), which similarly to TrkB, control the morphology of dendritic spines (Eithell et al., 2001; Gorsi et al., 2003; Horch and Katz, 2002; Horch et al., 1999; Klein, 2004; Penzes et al., 2003). Accordingly, Kidins220 is enriched at the postsynaptic density (Wu and Chao, personal communication), and dendritic-spine stability is significantly reduced in Kidins220–/– mice (Wu et al., 2009). It is interesting in this context that Kalirin has a major role in dendritic-spine morphogenesis (Caihill et al., 2009; Ma et al., 2003; Ma et al., 2008; Penzes et al., 2003; Penzes and Jones, 2008), suggesting a new connection by Kidins220 between these pathways.

In this light, the interaction of Kidins220 with Trio or other Trio/Kalirin family members is likely to be crucial to control neuronal differentiation and functions in vivo. The work presented here therefore might describe a basic molecular mechanism underlying this process. Thus, the scaffolding protein Kidins220 possesses all the prerequisites to co-ordinate different input signals from neurotrophins and ephrins with cytoskeletal rearrangements controlled by Trio/Kalirin and Rac1.

Materials and Methods

Plasmids

GFP-tagged Trio and RhoG were previously described (Estach et al., 2002), as were the GST-tagged CRIB domain of Pak1 and the KID1 domain of kinectin (Briandonn-Marjollet et al., 2008) and Vignal et al. (Vignal et al., 2001). The Raichu construct Rac1/Rac-CT containing the coding sequence of Rac1, Rac1 C-terminus and the GFP-tagged Trio and RhoG were previously described (Estrach et al., 2002), as were the pCAGGS expression vector, provided by Jun Miyazaki (Niwa et al., 1991). Plasmids

Materials and Methods

Cell culture and transfection

HeK293 cells were cultured in DMEM (Invitrogen) supplemented with 10% FBS and 0.1% HS. Since the expression of Kidins2201-402 was low, the quantity of DNA for each construct was optimised to achieve similar expression levels in the RhoGTPase activation assays (supplementary material Fig. S2A). The bleutthrough of the YFP channel into the FRET channel was assessed as a function of the Raichu construct (1

DNA constructs

Kidins220 1-1200bp (1-402 aa) and 1207-5289bp (403-1762 aa) were amplified by PCR using rat full-length Kidins220 eDNA (Iglesias et al., 2000) and the following primers: Kidins220 1-402 5′ primer, cat tca cec cgg gg tc gtt tta cca cag 3′ primer, gc gct ggg ctc tct ctc. DNA fragments were then ligated into the PacII/Sall sites of a HA-tagged pcDNA3.1 vector (Invitrogen). GST-tagged fragments of Trio (1-232 aa, 255-699 aa and 696-1203 aa) were subcloned from GFP-tagged Trio constructs (Estrach et al., 2002) into the pGEX4T2 (GE Biotech). DNA fragments were then ligated into the I sites of pGEX4T2 (GE Biotech).

Kidins220/ARMS binds Trio

Kidins220 protein purification

A DNA fragment encoding 1-402 aa of Kidins220 was inserted into a M15pQE31 vector (Qiagen) to generate a His6-tagged fusion protein. Protein expression was induced with 0.4 mM IPTG. Bacteria were grown for additional 3.5 hours at 25°C, pelleted, resuspended in 25 mM Tris-HCl, pH 7.8, 300 mM KCl, 2 mM 2-mercaptoethanol and protease inhibitors and lysed using a French press. After centrifugation, the pellet was resuspended in 8 M urea in PBS containing 0.05% Tween and after removal of cell debris, the supernatant was incubated with Ni-NTA agarose (Qiagen) at 25°C for 45 minutes. Beads were washed initially with 100 mM Neurobasal Medium (Gibco) with 2% B27 (Invitrogen). 10 minutes before fixation, neurons were treated with 0.1% FBS and fixed with 4% paraformaldehyde. The following antibodies were used for immunohistochemistry: mouse anti-Trio (1:2000, Santa Cruz), rabbit anti-Kalirin (US Biological), mouse anti-GFP (clone 3E1, CRUK), rabbit anti-α-tubulin (clone 8F10, clone 2E11), rabbit anti-RFP (Abcam), rabbit anti-synaptotagmin6 (STO112, CRUK), rabbit anti-SOD1 (Abcam), rabbit anti-Kalirin (US Biological), mouse anti-GFP (clone 3E1, CRUK), rabbit anti-activated caspase 3 (RD Systems), mouse anti-myc (clone 9E10, CRUK), goat anti-Ibrm (Santa Cruz) and mouse anti-RGS-Hi5 (Qiagen) antibodies. Alexa-Fluor 488-, 546- and 647-conjugated secondary antibodies were used from Molecular Probes.
Membrane cytosol fractionation

HEK293 cells transfected with the indicated constructs were scrapped into homogenisation buffer (20 mM HEPES-KOH, pH 7.2, 2 mM EDTA, 150 mM NaCl, supplemented with Roche Complete protease and phosphatase inhibitors), then lysed by passing the cells through a 27G needle. Cell lysates were centrifuged at 3500 g for 5 minutes at 4°C to pellet unbroken cells and nuclei. The postnuclear supernatant was centrifuged at 100,000 g (45,000 rpm, TL-A45 rotor) for 1 hour at 4°C. Membrane cytosol was resuspended in RIPA buffer (50 mM Tris-HCl, pH 7.2, 150 mM NaCl, 5% Triton X-100, 1% deoxycholate, 0.1% SDS). Finally, 1/50th of membrane and cytosol fractions were resolved by SDS-PAGE. PVDF membranes were probed with anti-syntaxin6 antibodies as a marker for the membrane fraction and with anti-SOD1 antibodies for the cytosol.

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Supplementary material available online at http://jcs.biologists.org/cgi/content/full/123/12/2111/DC1

References


Kidins220/ARMS binds Trio

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Table S1. Confirmed positive hits of the yeast-two hybrid screen

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<th>Protein description</th>
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<td>Aldehyde reductase</td>
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<tr>
<td>ANKRD27</td>
<td>BAB70755.1</td>
</tr>
<tr>
<td>APC subunit 2</td>
<td>AAF05751.1</td>
</tr>
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<td>ATPase inhibitor protein</td>
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<tr>
<td>Ca(^{2+})/calmodulin-dependent kinase II</td>
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<td>Erbin</td>
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<td>Zygin I</td>
<td>AAC71216.2</td>
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*This table summarises the positive clones obtained by screening a rat brain cDNA library using the N-terminal fragment of Kidins220 (Kidins220\(^{1-403}\)) in the AH109 yeast reporter strain.