A mitotic SKAP isoform regulates spindle positioning at astral microtubule plus ends

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.
A mitotic SKAP isoform regulates spindle positioning at astral microtubule plus ends

David M. Kern,1,2 Peter K. Nicholls,1 David C. Page,1,2,3 and Iain M. Cheeseman1,2

1Whitehead Institute for Biomedical Research, Cambridge, MA 02142
2Department of Biology, Massachusetts Institute of Technology, Cambridge, MA 02139
3Howard Hughes Medical Institute, Chevy Chase, MD 20815

The Astrin/SKAP complex plays important roles in mitotic chromosome alignment and centrosome integrity, but previous work found conflicting results for SKAP function. Here, we demonstrate that SKAP is expressed as two distinct isoforms in mammals: a longer, testis-specific isoform that was used for the previous studies in mitotic cells and a novel, shorter mitotic isoform. Unlike the long isoform, short SKAP rescues SKAP depletion in mitosis and displays robust microtubule plus-end tracking, including localization to astral microtubules. Eliminating SKAP microtubule binding results in severe chromosome segregation defects. In contrast, SKAP mutants specifically defective for plus-end tracking facilitate proper chromosome segregation but display spindle positioning defects. Cells lacking SKAP plus-end tracking have reduced Clasp1 localization at microtubule plus ends and display increased lateral microtubule contacts with the cell cortex, which we propose results in unbalanced dynein-dependent cortical pulling forces. Our work reveals an unappreciated role for the Astrin/SKAP complex as an astral microtubule mediator of mitotic spindle positioning.

Introduction

Mitosis requires assembly of the microtubule-based mitotic spindle to provide the structure and forces for cell division. Multiple molecular players associate with the cell division apparatus to facilitate spindle assembly and chromosome segregation. Previous work from our laboratory and others identified the Astrin/SKAP complex (Schmidt et al., 2010; Dunsch et al., 2011), which comprises Astrin (also referred to as Spag5), the dynactin light chain LC8, and the small kinetochore-associated protein SKAP/KNS (Fang et al., 2009; also referred to as C15orf23, Traf4af1, or Kinastrin). The Astrin/SKAP complex is highly expressed in mitosis (Whittleford et al., 2002; Fang et al., 2009; Thiru et al., 2014), where it localizes to aligned kinetochores and the mitotic spindle and plays multiple important roles, including in chromosome alignment and the maintenance of spindle bipolarity (Mack and Compton, 2001; Gruber et al., 2002; Thein et al., 2007; Manning et al., 2010; Schmidt et al., 2010; Dunsch et al., 2011). Although SKAP plays a central role within this complex, previous work found conflicting results for its functions and behavior. Here, we find that the SKAP isoform used in all previous studies of the human protein is exclusively expressed in mammalian testes, whereas mitotic cells instead express a shorter SKAP isoform. Our analysis of the mitotic SKAP isoform reveals a striking localization of this protein along the length of spindle microtubules and to microtubule plus ends, including to astral microtubules, suggesting potential roles for this complex beyond its previously defined functions in chromosome segregation.

Microtubules emanating from the spindle poles interact with two major subcellular sites: kinetochores and the cell cortex. Whereas kinetochores link microtubules to chromosomal DNA to direct chromosome segregation, the cell cortex anchors astral microtubules to the plasma membrane to generate cortical pulling forces that direct spindle positioning and orientation. Spindle positioning is critical for organismal development and cellular viability (Gönczy, 2008; Siller and Doe, 2009; Knoblich, 2010). The position of the mitotic spindle within a dividing cell establishes the cell division plane and the site of the cytokinetic furrow, thereby defining the relative sizes of the two daughter cells. The force to move the spindle within a cell is generated by the interaction of astral microtubule plus ends with the microtubule-based motor cytoplasmic dynein, which is localized to the cell cortex (Kiyomitsu and Cheeseman, 2012; Kotak et al., 2012; McNally, 2013; Kiyomitsu, 2015). Astral microtubules are a unique mitotic population of highly dynamic microtubules that originate from the centrosome and grow toward the cell cortex. When astral microtubules contact the cortex, dynein is thought to establish an “end-on” attachment and generate pulling force to move the spindle toward the cell cortex (Hendricks et al., 2012; Laan et al., 2012). The amount of pulling force on each side of the spindle is regulated through dynamic...
changes in the relative levels of cortical dynein (Collins et al., 2012; Kiyomitsu and Cheeseman, 2012). As a cell progresses from prometaphase into metaphase, the dynein motors on each side of the cell engage in a brief “tug-of-war” until the spindle is positioned at the cell center. In human cells, mitotic spindle position is controlled by both extrinsic and intrinsic cues (Fink et al., 2011; Kiyomitsu and Cheeseman, 2012). Much of the work on spindle positioning has focused on external or cortical factors, leaving open important questions regarding the function of astral microtubules. Although several microtubule plus-end proteins have been proposed to play roles in spindle positioning, including the end-binding (EB) proteins and Clasp1 (Rogers et al., 2002; Green et al., 2005; Samora et al., 2011; Bird et al., 2013), it remains unclear what protein components and properties of astral microtubule plus ends are required for their proper interactions with cortical dynein.

Our analysis reveals that the Astrin/SKAP complex plays important roles at astral microtubule plus ends for mediating proper spindle positioning. In cells with a plus-end tracking mutant of SKAP, chromosome segregation occurs normally, but metaphase spindles are dramatically mispositioned within the cell. We demonstrate that this spindle mispositioning occurs through an imbalance of forces generated by cortical dynein. SKAP plus-end tracking mutants display an apparent accumulation of lateral interactions between astral microtubules and the cell cortex. We propose that the Astrin/SKAP complex acts to mediate the proper connection between astral microtubule plus ends and cortical dynein.

## Results

### SKAP has both mitotic and testis/meiosis-specific isoforms

All previous studies on SKAP/KNSTRN have used a consensus annotated database protein sequence (ID: Q9Y448-1) with a predicted molecular mass of 34.5 kD. However, in analyzing the behavior of SKAP in human tissue culture cells, our affinity-purified anti-SKAP antibody detected a protein of $\sim$27 kD by SDS-PAGE and Western blotting (Fig. 1 A). Based on mass spectrometry analysis of endogenous SKAP isolated from HeLa cells, we were unable to detect peptides from a large region of the N terminus for the annotated SKAP protein (Fig. 1 B). In addition, in RNA-sequencing data from the Human BodyMap 2.0 database, we found that the only tissue with reads spanning the N terminus of the annotated SKAP protein (Fig. 1 B). Instead, the first defined exon 2. The shorter SKAP isoform generated using this downstream start codon has a predicted molecular mass of 26.9 kD, consistent with our mass spectrometry and Western blot analysis (Fig. 1, A and B; and Fig. S1 B). Although SKAP and its binding partner Astrin are conserved throughout vertebrates (Fig. S1 C), the longer, testis-specific SKAP isoform is present only in eutherian mammals (Fig. S1, B and C).

To visualize the relative expression of the short and long SKAP isoforms, we used two distinct antibodies: one that detects both isoforms of the human SKAP protein (Schmidt et al., 2010) and one that we generated against the testis-specific N-terminal extension of the mouse SKAP protein (Fig. S1 B). Based on Western blotting, the short SKAP isoform was present in mitotic (nocodazole-arrested) mouse 3T3 cells, juvenile (6-d-old) mouse testis, and adult (70-d-old) mouse testis, which represent cells or tissues with mitotic populations (Fig. S1 D; also see Fig. S1 E). In contrast, we found that the long SKAP isoform was present only in adult mouse testes, which have initiated sperm development (Fig. S1 D). In addition, immunostaining of adult mouse testes with the antibody specific to the long SKAP isoform revealed clear expression in elongating spermatids within the seminiferous epithelium (Fig. 1 D). This localization began as a punctate pattern throughout the DNA (Fig. 1 E) in testis developmental stage X (Russell et al., 1990), then spread to the cytoplasm and increased through stages XI and XII, persisting in stages I and II, before decreasing in stages III and IV (not depicted). In addition to the high levels of expression during late spermatogenesis, immunohistochemistry revealed localization of the testis-specific SKAP isoform to meiosis I spindles (Fig. S1 F) and weaker localization to meiosis II spindles (not depicted). We did not detect spindle localization of the testis-specific SKAP isoform in mitotic cells of the testis, attesting to both the timing of expression and the specificity of the antibody. We also note that recent work found that both the short and long SKAP isoforms detected by Western blotting and by immunostaining using the antibody we generated were abolished in SKAP-knockout mice, and SKAP-knockout mice displayed spermatogenesis defects (Grey et al., 2016). Thus, SKAP is expressed as two isoforms with distinct transcriptional start sites, resulting in a shorter mitotic form (which we will refer to as “short SKAP”) and a longer testis-specific form (which we will refer to as “long SKAP”).

### Short SKAP, but not long SKAP, is fully functional to facilitate mitosis

Prior studies on SKAP function in mitosis have relied on unreccued RNAi-based depletions (Schmidt et al., 2010) or ectopic expression of long SKAP (Lee et al., 2014; Tamura et al., 2015). With knowledge of these two SKAP isoforms, we next tested the functionality of each isoform in mitotic human cells by conducting rescue experiments. After SKAP depletion by RNAi (Figs. 2 A and S2 A), we observed dramatic defects in mitosis, including cells with highly misaligned chromosomes, disorganized spindles, and multipolar spindles that are a result of premature centrosome splitting based on Centrin localization (Fig. 2, B–E; and Video 1; also see Schmidt et al., 2010; Dunsch et al., 2011). Expression of an RNAi-resistant version of the long (testis-specific) SKAP isoform was unable to rescue these defects (Fig. 2, B, C, and F; and Fig. S2, B and C; also see Materials and methods). In contrast, expression of the short SKAP isoform fully rescued SKAP depletion as assessed by proper spindle assembly and timing (Fig. S2 B), chromosome alignment (Fig. 2, B and C), bipolar spindle assembly, and mitotic timing from nuclear envelope breakdown to anaphase (Figs. 2 E and S2 E). Therefore, the short (mitotic) isoform, but not the long (testis) isoform, rescues SKAP depletion defects in mitosis, demonstrating that these isoforms represent functionally distinct proteins.
To investigate the basis for this functional difference, we analyzed the associations and subcellular localization of the two SKAP isoforms as exogenously expressed GFP fusions (for a complete list of cell lines, see Table S1). We found that both long and short SKAP displayed largely similar interacting partners, including the other Astrin/SKAP complex components (Fig. S2 D). However, despite these similar interactions, the SKAP isoforms displayed distinct localization (Fig. 2 F, Video 2, and Fig. S2 F). In interphase cells, long SKAP-GFP displayed weak microtubule localization, as well as localization to punctate foci throughout the cytoplasm. In contrast, short SKAP-GFP displayed clear localization to microtubule plus ends in interphase cells. In mitosis, a GFP fusion to the long SKAP isoform localized to kinetochores, centrosomes, and spindle microtubules (Fig. 2 F), consistent with previous work (Schmidt et al., 2010). The short isoform of SKAP also localized to aligned kinetochores, spindle microtubules, and centrosomes in mitotic cells. However, the spindle localization of short SKAP was more intense along microtubule lengths and additionally displayed a speckled pattern typical of plus-end tracking proteins (Fig. 2 F), consistent with the interphase data. Therefore, the testes-specific long SKAP isoform is able to associate with the other components of the Astrin/SKAP complex when expressed ectopically in tissue culture cells, but displays distinct localization behavior. As such, long SKAP could act in a dominant manner by replacing endogenous short SKAP within the Astrin/SKAP complex, potentially explaining the defects reported previously for high-level ectopic expression of long SKAP (Lee et al., 2014; Tamura et al., 2015). Together, these analyses demonstrate that the two SKAP isoforms exhibit differential localization in mitotic cells, and that only the shorter SKAP isoform is fully functional to facilitate the multiple roles of SKAP during mitosis.

SKAP microtubule-binding activity is necessary for Astrin/SKAP spindle localization and chromosome segregation

The short, mitosis-specific SKAP isoform displays localization both along the length of microtubules and to microtubule plus ends. To dissect the contributions of this localization to SKAP function, we first sought to completely eliminate the microtubule-binding activity in SKAP. SKAP contains a C-terminal coiled-coil region (Fig. 3 A), which we predicted would be responsible for the association of SKAP with the Astrin/SKAP complex, and an N-terminal region with a patch of positively charged residues immediately preceding the coiled coil that is well suited for associating with negatively charged microtubules. Cells in which endogenous SKAP was replaced by either a SKAP mutant lacking the entire N-terminal region (ΔNT) or a more specific mutant in which a cluster of five
positively charged residues was targeted to reverse these charges (SKAP 5xD; Fig. 3 A) resulted in severe defects in chromosome alignment and spindle assembly (Fig. 3, B and C; and Fig. S2 G), similar to those observed after SKAP depletion. In addition, these SKAP ΔNT and 5xD mutants disrupted SKAP microtubule localization but did not prevent SKAP localization to kinetochores (Fig. 3, D and E). However, when quantifying cells with aligned metaphase plates, we did detect a similar relative reduction in kinetochore localization for Astrin in both SKAP-depleted cells and the SKAP microtubule-binding mutants (Fig. 3 E, bottom). Therefore, although SKAP microtubule binding is not strictly necessary for Astrin/SKAP complex kinetochore localization, it contributes to full complex localization at aligned kinetochores. Together, these data indicate that SKAP contains a major microtubule-binding activity of the Astrin/SKAP complex, and that this microtubule binding is critical for the spindle localization and function of this complex.

The short SKAP isoform displays robust plus-end tracking in mitosis

We next sought to precisely analyze the plus-end tracking activity of SKAP. Prior studies on the Astrin/SKAP complex reported plus-end tracking for GFP-Astrin expressed in interphase cells (Dunsch et al., 2011) and identified an interaction between SKAP and EB1 (Wang et al., 2012; Tamura et al., 2015). However, those previous studies did not report a plus-end tracking activity for SKAP in cells. Indeed, we found that the long SKAP isoform did not display robust plus-end tracking activity in interphase or mitosis (Fig. 2 F, Video 2, and Fig. S2 F), possibly because of steric effects or protein instability caused by the N-terminal extension present in long SKAP (Fig. S1 B). In contrast, the short SKAP isoform displayed spindle localization and fluorescent speckles along microtubules indicative of microtubule plus-end tracking (Fig. 2 F, Video 2, and Fig. S2 F). Using live cell imaging, we observed clear localization for short (mitotic) SKAP-GFP to growing microtubule plus-ends (Fig. 4, A and B; and Video 3). In addition, we found that the SKAP and Astrin plus-end signals trailed the extreme tip of the EB1 “comet” in both mitosis and interphase (Figs. 4 C and S3 A), potentially because of the additional microtubule-binding capability of the Astrin/SKAP complex and in agreement with previous studies for Astrin localization (Dunsch et al., 2011).

The plus-end tracking behavior for the Astrin/SKAP complex was dependent on the EB SKAP Sx[I/L]P motif (Honnappa et al., 2009), as mutation of the SKAP EB-interacting motif from SLLP to SLNN (here termed “SKAP ΔEB”) eliminated...
Astrin/SKAP complex regulates spindle position

Kern et al.

Both SKAP and Astrin plus-end tracking (Fig. 4, B and C; and Fig. S3 A). Importantly, despite eliminating this plus-end tracking activity, the SKAP ΔEB mutant localized to both kinetochores and microtubules, even in the absence of endogenous SKAP (Fig. 4 D). We note that this result for short SKAP localization is different from that reported for long SKAP by others (Tamura et al., 2015), in which a comparable ΔEB mutant also eliminated SKAP microtubule localization. We suspect that long SKAP has reduced capacity to bind and track microtubules, which is consistent with our localization and phenotypic analysis (Fig. 2). Together with our analysis of the SKAP microtubule-binding mutants described earlier, this indicates that SKAP possesses independent microtubule-binding activity in addition to its association with EB family proteins.

To test the role of the SKAP microtubule plus-end tracking behavior in mitotic cells, we next investigated the functional consequences of replacing endogenous SKAP with the short SKAP ΔEB mutant (Fig. S3 B). In contrast to the catastrophic chromosome segregation defects that prevent microtubule localization observed in SKAP mutants (Fig. 3 C), we found that the SKAP ΔEB mutant was able to rescue the depletion of endogenous SKAP for its ability to facilitate proper chromosome localization and track microtubules.
alignment and segregation (Fig. 4, D and E) with normal mitotic timing (Fig. 4 F). Therefore, we conclude that Astrin/SKAP plus-end tracking is not necessary for the key chromosome alignment functions of this complex.

**Astrin/SKAP localization to microtubule plus ends is necessary for proper spindle positioning**

Although the SKAP ΔEB mutant was able to facilitate normal chromosome segregation, during our analysis of chromosome alignment, we unexpectedly observed that many spindles in the SKAP ΔEB mutant were dramatically mispositioned away from the cell midzone, often adjacent to or abutting the cell cortex (Fig. 5 A). In these extreme cases, cells appeared to have centrosomes and their astral microtubules directly in contact with the cortex (Fig. S3 C). In control cells or cells in which wild-type SKAP rescued endogenous SKAP depletion, we found that the spindle was typically positioned symmetrically within the dividing cells with similar distances between each spindle pole and the cell cortex (mean spindle displacement: control, 0.62 μm; rescue, 0.87 μm; Fig. 5 A). In contrast, we found that the spindle was positioned asymmetrically within the cell in SKAP ΔEB mutant cells such that one spindle pole was often much closer to the cell cortex (mean spindle displacement: ΔEB, 2.1 μm; Fig. 5 A), including cells with extremely mispositioned spindles (Fig. 5 A). Expression of the SKAP ΔEB mutant without depletion of the endogenous protein resulted in a modest, but statistically significant, shift in spindle positioning (mean spindle displacement: ΔEB, 1.05 μm; Fig. 5 A), potentially because of the formation of mixed Astrin/SKAP complexes. SKAP-depleted cells display dramatic and pleiotropic defects in chromosome alignment and centrosome stability (Fig. 2), which can influence spindle positioning indirectly (Kiyomitsu and Cheeseman, 2012; Tame et al., 2016), thereby preventing a directed analysis of spindle positioning phenotypes in SKAP-depleted cells with more extreme phenotypes (see Video 1). To test for spindle positioning defects in SKAP-depleted cells without substantial secondary defects, we quantified cells with clearly defined metaphase plates, which likely represent cells with an intermediate SKAP depletion. In these depleted cells, we found substantial spindle mispositioning (mean spindle displacement: ΔEB, 1.62 μm; Fig. 5 A), although slightly less than that observed in the SKAP ΔEB mutant. We conclude that SKAP ΔEB mutant replacement has a potent and specific effect on spindle positioning.
To determine the nature of this spindle positioning defect, we next asked whether the mispositioning in the SKAP ΔEB mutants depended on the defined components of the spindle positioning pathway: astral microtubules and cortically localized dynein. Eliminating astral microtubules using low-dose nocodazole treatment (Théry et al., 2005) prevented spindle mispositioning in the SKAP ΔEB mutant (Fig. 5 B). Similarly, depletion of LGN, an upstream cortical recruitment factor for dynein that is required for cortical dynein localization in metaphase (Kiyomitsu and Cheeseman, 2012), eliminated the spindle positioning defects observed for the SKAP ΔEB mutant, resulting instead in a central spindle position (Fig. 5 C). These results demonstrate that aberrant and unbalanced forces generated by astral microtubules and cortical dynein lead to the dramatic spindle positioning defects in the absence of Astrin/ SKAP localization to microtubule plus ends.

Based on time-lapse imaging of mitotic cells, SKAP ΔEB mutant cells displayed a directed shift in the position of the metaphase plate toward the cell cortex, usually shortly after chromosome congression (Fig. 5 D and Video 4). These rapid and directed movements are different from the slow spindle oscillations with a narrow amplitude that we have described previously as promoting a central spindle position (Kiyomitsu and Cheeseman, 2012). Such SKAP ΔEB mutant cells entered anaphase with mispositioned spindles but were able to subsequently position the spindle during early anaphase, consistent with an anaphase correction pathway (Kiyomitsu and Cheeseman, 2013). Thus, microtubule plus-end tracking by the Astrin/ SKAP complex is necessary for metaphase spindle positioning.

The SKAP plus-end tracking mutant alters astral microtubule behavior at the cell cortex

The SKAP ΔEB mutant phenotype could be explained by a failure of dynein to delocalize from the cell cortex as the spindle approaches (Kiyomitsu and Cheeseman, 2012), leading to enhanced spindle forces on one side of the cell. Therefore, we tested whether SKAP ΔEB mutants displayed a misregulation of cortical dynein localization. Using the dynactin subunit p150Glued as a marker of dynein/dynactin localization (Kiyomitsu, 2015), we did not observe a change in cortical localization behavior in the SKAP ΔEB mutant. Similar to what we
have reported previously for dynein in control cells (Kiyomitsu and Cheeseman, 2013), p150Glued was able to localize to the cell cortex, but when the spindle was significantly shifted to one side of the cell, p150Glued displayed substantially higher localization to the opposite cell cortex (Fig. 6A).

In metaphase, the plus ends of astral microtubules contact the cell cortex, but microtubule–cortical contacts typically persist for only a few seconds before growth ceases and the microtubules depolymerize (Samora et al., 2011). Indeed, we only rarely detected microtubule plus ends in proximity to the cell cortex based on EB1 staining in control cells. In contrast, in SKAP ΔEB mutant cells in which we observed significant spindle shifts, we also observed an accumulation of apparent lateral contacts between growing astral microtubules and the cell cortex (Fig. 6C; also see Fig. 5, A–C; and Fig. S3, C and D). Based on imaging of microtubule plus ends marked by EB3-tomato in live cells, we found that in the SKAP ΔEB mutant, astral microtubules often grew along the cell cortex (Fig. 6D and Videos 5 and 6). This lateral astral microtubule growth increased as the spindle approached the cortex. In cells with substantially shifted spindles, most astral microtubules close to the cortex exhibited lateral cortical growth, whereas astral microtubules on the opposite side generated cortical contacts less frequently (Fig. 5, A–C; Fig. 6C; Fig. S3 D; and Videos 5 and 6). We conclude that Astrin/SKAP complex localization to microtubule plus ends plays an important role in astral microtubule behavior and is required for proper interactions between astral microtubules and cortical dynein to promote spindle positioning.

The Astrin/SKAP complex binds to and regulates Clasp1 in mitosis

To explore the basis for this spindle positioning phenotype, we next generated an interaction map by conducting multiple immunoprecipitations of Astrin and SKAP from mitotic cells. We found that the Astrin/SKAP complex interacts either directly or indirectly with multiple key proteins that function in microtubule organization and spindle positioning, including Clasp1, Plk1, NuMA, and dynein (Fig. S4 A). Previous work found that Clasp1 plays an important role in microtubule–cortex interactions, spindle positioning, and astral microtubule behavior (Mimori-Kiyosue et al., 2005; Ambrose and Wasteneys, 2008; Samora et al., 2011; Bird et al., 2013). Indeed, Samora et al. (2011) observed spindle mispositioning after Clasp1 depletion. Therefore, we followed up on our results (Schmidt et al., 2010) and previous studies of an interaction between full-length Clasp1 and Astrin (Maffini et al., 2009; Manning et al., 2010). We found that the C-terminal domain of Clasp1 (Maiato et al., 2003), which localizes in mitosis to kinetochores, the spindle, and the cell cortex (Fig. 7 A), was sufficient to communo-precipitate significant amounts of the Astrin/SKAP complex.
Astrin/SKAP complex regulates spindle position

Kern et al. 323

(Fig. 7 B). The Clasp1 C terminus also coimmunoprecipitated previously defined interacting partners including CLIP1/CLIP-170 and CENP-E (Patel et al., 2012), as well as dynein machinery (Fig. 7, A and B). However, affinity purification of the Clasp1 C terminus did not isolate peptides from full-length Clasp1, indicating that this construct is not multimerizing with endogenous Clasp1 and therefore narrowing down the Clasp1 binding region that is sufficient for the Astrin/SKAP complex interaction. To further define the basis for this interaction, we found that ectopically expressed SKAP C-terminal coiled-coil construct was immunoprecipitated by the Clasp1 C terminus (Fig. S4 C), suggesting that Clasp1 interacts with the intact Astrin/SKAP complex but not its microtubule-binding domain.

We next tested the relationship between Clasp1 and SKAP for their localization to microtubules. In control cells, Clasp localized to kinetochores, the spindle, and microtubule plus ends during mitosis (Fig. 7 C). However, in the SKAP ΔEB mutant, we observed a reduction in spindle-bound Clasp and in Clasp localized to microtubule plus ends (Fig. 7, C and D). In contrast, SKAP depletion had no noticeable effect on Clasp plus-end microtubule localization in interphase cells (Fig. S4 B). In reciprocal experiments, we found that SKAP localized normally to microtubules and microtubule plus ends after the individual or simultaneous depletion of Clasp1 and Clasp2 (Fig. 7 E and Fig. S4, C and D). These results indicate that the Astrin/SKAP complex associates with Clasp1 and contributes to its localization in mitosis, including its robust localization to astral microtubule plus ends. In all, we demonstrated that the Astrin/SKAP complex displays multiple activities that may contribute to the connection between astral microtubules and the cell cortex. These include its intrinsic microtubule-binding activities, its association with Clasp1, and interactions with cytoplasmic dynein and dynein-associated proteins (Figs. 7 B and S4 A). The proper targeting of these Astrin/SKAP complex activities to microtubule plus ends is critical for the proper regulation of metaphase spindle position.

Discussion

We demonstrated that SKAP exists as two distinct transcriptional isoforms and analyzed the novel SKAP isoform in mitosis, which revealed an unexpected role in mitotic spindle positioning. Because the testis SKAP isoform is present only in eutherian mammals (Fig. S1 C) and shows marked sequence divergence even between mammals, it is possible that it has acquired new roles only recently in evolution. For example, it is possible that the N-terminal SKAP extension in testis modifies the structure and behavior of SKAP or facilitates interactions with testis-specific proteins. We note that previous papers from...
our laboratory and others have conducted studies on the function of SKAP in mitosis using the longer, testis-specific SKAP isoform (Schmidt et al., 2010; Dunsch et al., 2011; Wang et al., 2012; Lee et al., 2014; Tamura et al., 2015). Because this long isoform displays a large reduction or complete loss of microtubule plus-end tracking activity and a reduction in spindle localization and is unable to rescue endogenous SKAP depletion (Schmidt et al., 2010; Dunsch et al., 2011; Wang et al., 2012, 2015). Our work adds the Astrin/SKAP complex to the list of bona fide astral microtubule plus-end trackers. In addition to the localization of SKAP to microtubule plus ends, we found that the Astrin/SKAP complex associates with diverse proteins that play roles in spindle positioning, including astral microtubules in metaphase are characterized by transient growth and rapid turnover. Instead of mediating a stable connection with the cell cortex, astral microtubules only occasionally and briefly contact the cortex (Samora et al., 2011). These brief contacts allow cortically localized dynein to use the astral microtubules for transient force generation to drive spindle positioning. This creates a spindle centering system that is rapid and can be quickly regulated by changes in either astral microtubule behavior or cortical dynein recruitment. Interestingly, in the SKAP ΔEB mutant, astral microtubules are altered such that they appear to accumulate lateral, instead of end-on, cortical interactions. We propose that these laterally growing astral microtubules generate more persistent connections with cortical dynein. Because of the persistence of these force-generating interactions, the centrosome closer to the cortex would rapidly obtain a force advantage and the spindle would be pulled to one side of the cell (Fig. 8A). As the spindle moves toward one side of the cell, the astral microtubules from the distal spindle pole would no longer be able to interact with the far cell cortex, preventing cells from correcting this imbalance, even though cortical dynein localization is still regulated to reduce its localization in the vicinity of the spindle pole (also see Kiyomitsu and Cheeseman, 2012). Thus, we propose that defective astral microtubule interactions with the cell cortex result in the dramatic spindle mispositioning defects that we observed in the SKAP ΔEB mutant. Recent work has described the basis for cortical dynein recruitment and the extrinsic and intrinsic cues that control spindle positioning (Kiyomitsu, 2015). Our work additionally establishes astral microtubule plus-end factors as critical players in spindle positioning.

Astral microtubules have an array of plus end–associated proteins that modify their behavior (Akhmanova and Steinmetz, 2008, 2015). Our work adds the Astrin/SKAP complex to the list of bona fide astral microtubule plus-end trackers. In addition to the localization of SKAP to microtubule plus ends, we found that the Astrin/SKAP complex associates with diverse proteins that play roles in spindle positioning, including...
Clasp1 and dynein/dynactin Maiato et al., 2003; Samora et al., 2011; Duellberg et al., 2014). We found that Clasp1 behavior is regulated in mitosis by Astrin/SKAP complex, which may contribute to promoting proper astral microtubule behavior and cortical–microtubule interactions. The combined interactions and activities of these and other proteins may create a modular complex that plays a specific role upon cortical contact (Fig. 8 B). A critical challenge for future work is to define the nature of this astral microtubule–cortical attachment, including the composition and regulation of the astral microtubule plus ends and the activities required for microtubule–dynein engagement and force generation.

**Materials and methods**

**Cell line generation**

HeLa Flp-In cells were generated using HeLa LacZero/TO cells (a gift from S. Taylor, University of Manchester, Manchester, England, UK) and pCDNAS-FRT-TO–based plasmids (Invitrogen). For untagged SKAP constructs with a GFP expression reporter, we generated a vector by fusing the IRES and eGFP sequences from the pIRES2-eGFP vector (Clontech) after the open reading frame of the pCDNAS-FRT-TO–based plasmid. Cell lines were made using Flp recombinase–mediated integration based on the manufacturer instructions for the Flp-In TReX System (Invitrogen). Clonal cell lines from retroviral infection were made as described previously (Cheeseman et al., 2004). Cell lines (HeLa, HeLa Flp-In, and 3T3) were maintained in DMEM supplemented with 100 U/ml streptomycin, 100 U/ml penicillin, 2 mM glutamine, and 10% (vol/vol) FBS. Flp-In lines were cultured in HyClone FBS without tetracycline.

**Protein depletion, induction, and BacMam expression**

For siRNA transfection, we used Lipofectamine RNAiMAX (Invitrogen) and OptiMEM (Gibco). For protein depletion, we used ON-TARGET (Clontech) after the open reading frame of the pCDNA5-FRT-TO–LV system. Clonal cell lines from retroviral infection were made as described previously (Cheeseman et al., 2004). Cell lines (HeLa, HeLa Flp-In, and 3T3) were maintained in DMEM supplemented with 100 U/ml streptomycin, 100 U/ml penicillin, 2 mM glutamine, and 10% (vol/vol) FBS. Flp-In lines were cultured in HyClone FBS without tetracycline.

**Antibody generation**

The antibody to detect the mouse long SKAP N terminus was raised against GST-mouse long SKAP (aa 1–78), affinity purified using the same protein, and depleted for GST-specific antibodies using a GST column. The affinity-purified human Astrin antibody used for IP–mass spectrometry and immunofluorescence (IF) was raised against Astrin (aa 955–1,193-His) and purified using (aa 965–1,193-His). Antibody affinity purification was performed as described previously (Desai et al., 2003).

**IF and Western blotting**

IF and Western blotting (WB) were conducted using antibodies against human SKAP (Schmidt et al., 2010; 1:2,000 for IF, 1:4,000 for WB), rabbit anti-mouse SKAP N terminus (this study; 1:400 IF, 1:1,000 WB), tubulin (for human cell experiments: DM1a: Sigma-Aldrich; 1:1,000 for IF, 1:2,000 for WB; for mouse cell experiments: T5186; Sigma-Aldrich; 1:1,000 for IF, 1:2,000 for WB), Centrin2 (Backer et al., 2012; 1:12,000 for IF), rabbit anti-Astrin (Yang et al., 2006; diluted from media for IF), mouse anti-EB1 (5/EB1; BD Transduction Laboratories; 1:250), rabbit anti-EB1 (H-70; Santa Cruz Biotechnology; 1:200), Clasp (Xorbit; 1:2,000 for IF; a gift from R. Heald, University of California, Berkeley, CA; Hannak and Heald, 2006), p150<sup>glued</sup> (1:150Glued; BD Transduction Laboratories; 1:250), goat anti-GFP (a gift of A. Ladurner, Ludwig Maximilians University of Munich, Munich, Germany; 1:2,000 for WB), and centromeres (ACA Antibodies; 1:100). For immunofluorescence, cells were plated on glass coverslips coated with poly-L-lysine (Sigma-Aldrich). For nocodazole experiments, the indicated concentration of nocodazole (Sigma-Aldrich) or vehicle control was added to cells for 1 h before fixation (47 h after siRNA addition). Fixation conditions were as follows: For IF with SKAP or Astrin visualized at kinetochores (Figs. 2 A, 3 C, 4 D, and S3 B), cells were first preex-tracted for 5 min in 0.1% Triton X-100 in PHEM buffer (60 mM Pipes, 25 mM Hepes, 10 mM EGTA, and 4 mM MgSO<sub>4</sub>, pH 7), followed by fixation for 10 min in 4% formaldehyde in PHEM buffer. For IF with microtubules visualized (including all experiments with spindle shifts quantified in Fig. 5), cells were fixed for 10 min in 4% formaldehyde in PHEM buffer. For IF with p150<sup>glued</sup>, cells were fixed in PBS with 2% sucrose and 3% formaldehyde. For IF with EB1 or Centrin2 antibodies, cells were fixed for 5 min in methanol at −20°C. All other fixation steps were performed at RT immediately after removal from 37°C incubator. Blocking and primary antibody dilutions were performed using AbDil (20 mM Tris, 150 mM NaCl, 0.1% Triton X-100, 3% BSA, and 0.1% NaN<sub>3</sub>, pH 7.5). Washing and secondary antibody dilution steps were performed in PBS plus 0.1% Triton X-100 (PBS-TX). Cy2-, Cy3-, and Alexa Fluor 647–conjugated secondary antibodies (Jackson Immunoresearch Laboratories) were used at 1:300. DNA was visualized by incubating cells in 1 µg/ml Hoechst-33342 (Sigma-Aldrich) in PBS-TX for 2 min followed by PBS-TX rinsing. Coverslips were mounted using PPDM (0.5% p-phenylenediamine and 20 mM Tris-Cl, pH 8.8, in 90% glycerol).

**SKAP models and phylogeny**

The SKAP gene model (Fig. 2 B) was generated using the Integrated Genomics Viewer (Robinson et al., 2011) with data from Human BodyMap 2.0 (Illumina). SKAP proteins were aligned and visualized using Jalview software (Robinson et al., 2011). Phylogenetic tree was made using data from TreeBase (Hedges et al., 2006).

**Live and fixed-cell imaging**

Fixed-cell and live cell images were acquired on a DeltaVision Core microscope (Applied Precision) equipped with a CoolSnap HQ2 CCD
camera (Photometrics). Images were deconvolved and planes projected (maximum intensity) as noted in the figure legends. Paired images are scaled equivalently unless otherwise noted. Fixed cells were imaged using a 100×, 1.4-NA U-PlanApo objective (Olympus). For live-cell imaging, cells were plated on 35-mm glass-bottom microwell dishes (MatTek) and imaged in CO₂-independent media (Invitrogen) with 100 ng/ml Hoechst-33342 (Sigma-Aldrich) at 37°C. For mitotic timing/phenotype videos, to assess the IRES GFP reporter, points were selected and imaged before video start. For video imaging, points were imaged with three Z-sections 5 µm apart using fluorescent and transmitted light at the lowest level usable for data collection. Images were collected at 5-min intervals for 8 h using a 40×, 1.35-NA U-PlanApo objective (Olympus). For EB3-tTomato videos, GFP-positive (transgene expressing) cells were selected and the 100× objective was used to collect images every 2 s for 60 s with a 0.5-s exposure time. Spinning disc confocal videos were taken with a Ti-E inverted microscope (Nikon) using a Revolution laser system (Andor) using an iXon 897E EMCCD camera (Andor) in a 37°C chamber. Images were collected every 0.5 s for 30 s with a 240-ms exposure time. Images and videos were processed using Softworx (Applied Precision), Metamorph (Molecular Devices), ImageJ/Fiji, and Photoshop/Illustrator software (Adobe). Distance measurements for quantifications were made using Softworx and then plotted and analyzed using Prism (GraphPad). Kinetochore intensity measurements were made using Metamorph. Projected image stacks (maximal intensity) were quantified by selecting regions with kinetochores and nearby regions for background subtraction. Kymographs and line scans were generated using Metamorph. Statistical analyses (two-tailed t tests) were performed using Prism software where indicated.

Mouse immunostaining
Wild-type 129S2/SvPasCrl mice were purchased from Charles River Laboratories. All animals were housed at the Whitehead Institute for Biomedical Research and maintained according to protocols approved by the Massachusetts Institute of Technology Committee on Animal Care. Adult male mice (60–70 d old) were killed in CO₂ and the tests were removed. For histologic analysis, tests were fixed in Bouin’s solution or 4% paraformaldehyde overnight and processed into paraffin wax, and 10-µm sections were cut and mounted on Superfrost slides. For immunohistochemistry, tissues were rehydrated and blocked in 5% normal donkey serum. Primary antibodies (mouse SKAP N terminus) were applied in PBS with 5% normal donkey serum overnight at 4°C. Immunolocalization was performed by fluorescing (using FITC-conjugated donkey anti–rabbit [Jackson ImmunoResearch Laboratories] and mounted using Prolong mounting media with DAPI [Molecular Probes]) or colorimetrically (using ImmPRESS HRP anti–Rabbit detection and developed with a DAB substrate kit [Vector Laboratories], counterstained with Harris’s hematoxylin, and mounted using Permount [Fisher Scientific]).

IP and mass spectrometry
For direct antibody IP (Figs. S2 D and S4 A), the indicated antibodies were coupled to beads as described previously (Cheeseman and Desai, 2005). For mitotic IP, unless otherwise noted, cells were arrested with nocodazole (Sigma-Aldrich) at 330 nM for 14 h and harvested by shake-off. For interphase IPs, mitotic cells were removed by shake-off and the remaining cells were harvested. GFPΔAP tagged proteins or endogenous proteins were isolated from HeLa cells as described previously (Cheeseman and Desai, 2005). Salt concentrations for bead binding and washing are indicated in the figure legends. Purified proteins were identified by mass LTQ XL Ion trap mass spectrometer (Thermo Fisher Scientific) using MuddPIT and SEQUEST software as described previously (Washburn et al., 2001). For the mouse testis IP, testes were collected as described earlier from one 3-mo-old mouse. Testes were then detunicated and resuspended in HeLa lysis buffer (Cheeseman and Desai, 2005) to a final volume of ~2 ml. For protease inhibition, one half of a Complete Mini, EDTA-free tablet (Roche) and 1 mM PMSF were added. This mix was subjected to Dounce homogenizer strokes until a suspension was achieved (as determined by light microscope). This mix was used with our standard localization and affinity purification (LAP) protocol (Cheeseman and Desai, 2005) using wash buffer with 150 mM KCl.

For IP followed by Western blot, 10-cm plates containing the LAP-Clasp1 C terminus stable cell line were incubated for 12 h with BacMam virus containing myc-SKAP (tag = MEQKLISeEDLGSS-) constructs. At 12 h, virus-containing media was replaced, and cells were incubated for 8 h before addition of 330 nM nocodazole. Cells were arrested in nocodazole for 15 h before harvest by shake-off. Each condition had ~2 million recovered cells. Cells were lysed by sonication in 0.5 ml IP-Western buffer (50 mM Hepes, pH 7.4, 150 mM KCl, 1 mM MgCl₂, 1 mM EGTA, and 0.05% NP-40 substitute) with added 1 mM β-glycerophosphate, 1 mM sodium orthovanadate, and 1 mM PMSF. Lysed cells were pelleted at 22,000 g for 10 min, and then 200 µl supernatant was bound for 2 h to 25 µl GFP-coupled beads (see LAP protocol) or 25 µl anti-myc (9E10)–coupled Sepharose beads (Co- Vance). Cells were rinsed three times in 500 µl IP-Western buffer and then washed twice for 5 min. Bound protein was eluted with 100 µl of 100 mM glycine at pH 2.6. Elutions and input samples were prepared with gel loading buffer and loaded for Western blotting. For Western blotting, the SKAP full-length and goat anti-GFP antibodies were used.

Online supplemental material
Fig. S1 shows SKAP alignment, phylogeny, and further SKAP isoform characterization in testes. Fig. S2 shows interphase interactions of SKAP and validation of the SKAP depletion and replacement protocols. Fig. S3 shows immunofluorescence of Astrin on mitotic plus ends, validation of the SKAP ΔEB mutant replacement experiment, and additional characterization of the astral microtubule phenotype. Fig. S4 shows data for Astrin and SKAP interactions in mitotic cells, validation of Clasp reagents, and further characterization of the Clasp interaction with the Astrin/SKAP complex. Video 1 depicts SKAP depleted cells going through mitosis. Video 2 compares interphase localization of the short and long SKAP isoforms. Video 3 shows localization of SKAP on mitotic plus ends by spinning disc microscopy. Video 4 shows examples of mitotic cells undergoing a spindle shift in the SKAP ΔEB condition. Video 5 shows EB3-marked plus ends in control, depletion, and replacement conditions. Video 6 shows additional EB3-marked plus ends in examples of SKAP ΔEB replacement cells. Table S1 lists cell lines used in this study. Online supplemental material is available at http://www.jcb.org/cgi/content/full/jcb.201510117/DCl.

Acknowledgments
We thank Tomomi Kiyomitsu, Terry Orr-Weaver, and members of Cheeseman, Page, and Burge Laboratories for their support and constructive comments; the Bioinformatics and Research Computing group at Whitehead for assistance with the analysis of SKAP isoforms; Wendy Salmon and the W.M. Keck Microscopy Facility at Whitehead for help with spinning disc microscopy; Dirk de Rooij for help with tests staining and identifying meiotic spindles; Corinne Grey and Bernard de Massy for discussions and sharing results before publication; and Rebecca Heald for suggesting and providing the Xorbit/Clasp1 antibody. P.K. Nicholls is a Hope Funds for Cancer Research Fellow supported by the Hope Funds for Cancer Research (HFCR-15-06-06) and the
recipient of an Early Career Fellowship [National Health and Medical Research Council GNT1053776]. This work was supported by a Scholar award to I.M. Cheeseman from the Leukemia and Lymphoma Society, a grant from the National Institutes of Health/National Institute of General Medical Sciences to I.M. Cheeseman (GM088313), and a Research Scholar grant to I.M. Cheeseman from the American Cancer Society (121776).

The authors declare no competing financial interests.

Submitted: 30 October 2015
Accepted: 30 March 2016

References


The authors declare no competing financial interests.

Cancer Society (121776).

Published May 2, 2016

Mol. Biol. Cell.


http://dx.doi.org/10.1083/jcb.200508180


