Maintaining the proper connection between the centrioles and the pericentriolar matrix requires *Drosophila* Centrosomin

Eliana P. Lucas and Jordan W. Raff

Wellcome Trust/Cancer Research UK Gurdon Institute, University of Cambridge, Cambridge CB2 1QN, England, UK

**Introduction**

Centrosomes comprise a pair of centrioles and a surrounding pericentriolar matrix (PCM). They are the major microtubule (MT) organizing centers (MTOCs) in animal cells and are thought to play an important part in organizing many cell processes, including cell polarity, cell migration, and cell division (Doxsey et al., 2005). Centrioles are also required for the formation of cilia and flagella (Basto et al., 2006), and they have important roles in many developmental processes (Davis et al., 2006). Not surprisingly, centriole or centrosome dysfunction has been implicated in a wide variety of human genetic diseases (Badano et al., 2005).

Although much is known about the protein composition of the centrosome, it remains unclear how centrosome structure and organization are maintained. In flies, the centrosomal protein Centrosomin (Cnn) is required to recruit several proteins to the centrosome (Megraw et al., 1999, 2001; Vaizel-Ohayon and Schejter, 1999; Terada et al., 2003). In *cnn* mutant embryos, and in somatic cells lacking Cnn, the centrosomes fail to function as MTOCs during mitosis and anastral spindles assemble through a centrosome-independent pathway. This leads to severe mitotic defects in embryos and to errors in centriole segregation in somatic cells. The Cnn-related protein CDK5RAP2 is linked to microcephaly in humans, but *cnn* mutant brains are of normal size, and we observe only subtle defects in the asymmetric divisions of mutant neuroblasts. We conclude that Cnn maintains the proper connection between the centrioles and the PCM; this connection is required for accurate centriole segregation in somatic cells but is not essential for the asymmetric division of neuroblasts.

Correspondence to Jordan W. Raff: j.raff@gurdon.cam.ac.uk

Abbreviations used in this paper: Cnn, centrosomin; GSC, germline stem cell; MT, microtubule; MTOC, MT organizing center; NB, neuroblast; NEB, nuclear envelope breakdown; PCM, pericentriolar matrix; WT, wild-type.

The online version of this article contains supplemental material.
Results and discussion

Centrioles recruit PCM components and MTs but cannot maintain their connection to them in the absence of Cnn

In fixed embryos and somatic cells that lack Cnn, PCM components are barely detectable at the poles of the mitotic spindles (Megraw et al., 1999, 2001; Vaizel-Ohayon and Schejter, 1999). Centrioles are still present in cnn mutant cells (Megraw et al., 2001), but their function and positioning within the centrosome have not been analyzed. To understand better how Cnn normally recruits PCM components to the centrioles, we generated transgenic Drosophila lines expressing an mRFP-centriolar marker (either mRFP-Fzr or mRFP-PACT), together with one of three PCM markers fused to GFP: Aurora A–GFP, Grip75-GFP (a component of the γ-tubulin ring complex), and GFP-D-TACC. It has previously been shown that Cnn can interact with both the γ-tubulin ring complex and Aurora A (Terada et al., 2003), but we found no evidence for an interaction between Cnn and D-TACC in coimmunoprecipitation experiments (unpublished data).

In wild-type (WT) syncytial embryos, centrioles recruited approximately equal amounts of PCM at all stages of the rapid mitotic cycles, and they remained well centered within the PCM throughout the cell cycle (Fig. 1; Fig. S1; and Videos 1 and 2, available at http://www.jcb.org/cgi/content/full/jcb.200704081/DC1). During interphase, the centrioles were always closely associated with the nuclear envelope, whereas in mitosis, they were always closely associated with the spindle poles (Videos 1 and 2).

In embryos laid by cnn homozygous females (hereafter, cnn embryos), we were surprised to observe that the centrioles were associated with appreciable amounts of PCM, but they were often not properly centered within it (Fig. 1; Fig. S1; and Videos 1 and 2). In video recordings of cnn embryos, the centrioles appeared to be constantly nucleating PCM but seemed unable to maintain their connection to it. The centrioles often exhibited irregular, stochastic movements, leaving a trail of PCM behind them as they moved away. This PCM trail was most easily seen in cnn embryos expressing GFP–D-TACC (Video 1), as this protein was recruited in particularly large amounts to the centrioles, and large clusters of GFP-D-TACC often remained in the cytoplasm for some time after the centrioles had moved away. Smaller amounts of
Aurora A–GFP and Grip75-GFP were recruited to the centrioles (Video 2), and so only small amounts of these proteins remained associated with the centrioles as they moved around the embryo. As a result of this abnormal centriole behavior, the centrioles in cnn embryos often lost their attachment to the nuclear envelope in interphase and to the spindle poles in mitosis. We refer to this behavior of the centrioles as “centriole rocketing” (see the following section).

Previous studies suggested that centrosomes lacking Cnn fail to function as MTOCs during mitosis (Megraw et al., 1999, 2001; Vaizel-Ohayon and Schejter, 1999; Mahoney et al., 2006). We therefore examined whether the PCM organized by the centrioles in cnn embryos was capable of nucleating MTs. As shown in Fig. 2 (A–D) and Videos 3 and 4 (available at http://www.jcb.org/cgi/content/full/jcb.200704081/DC1), the centrosomes in cnn embryos organized astral MT arrays but seemed unable to maintain their connection with them. When the embryos entered mitosis, many nuclei were not associated with centrioles, and anastral spindles assembled around the mitotic chromatin (not depicted). Many nuclei, however, were close enough to a centriole for the astral MTs to contribute to spindle assembly (Fig. 2 D, arrow). Often, however, these centrioles failed to maintain their position at the spindle pole and either wandered around within the spindle (Fig. 2 D, red arrowhead) or lost their connection to the spindle altogether (Fig. 2 D, yellow arrowhead). We conclude that the dramatic mitotic defects observed in cnn embryos do not result from a failure of the centrioles to recruit PCM, or of the centrosomes to nucleate astral MTs, but instead result from the failure of the centrioles to maintain a stable connection to the PCM and MTs that they organize.

**Centriole rocketing in cnn embryos is MT dependent**

The centriole rocketing appeared to be driven by the asymmetric organization of the PCM and MTs around the centrioles (Videos 1–3). To test whether the rocketing was MT dependent, we injected the MT-depolymerizing drug colchicine into embryos. In WT embryos in late interphase, the centrioles had already migrated around the nuclei and, when we plotted their movement over time, the centrioles moved regularly across the embryo cortex (Fig. 2 E and Video 5, available at http://www.jcb.org/cgi/content/full/jcb.200704081/DC1). This regular movement of the centrosomes and their associated nuclei across the cortex is driven by actin- and myosin-dependent cortical contractions, and it continued after colchicine injection (Video 5). In contrast, when we plotted centriole movement in cnn embryos in late interphase, we observed the rocketing behavior described previously (Fig. 2 F and Video 5). The rocketing ceased after colchicine injection, and the centrioles reverted to a regular movement across the embryo cortex (Fig. 2 G and Video 5). Thus, centriole rocketing in cnn embryos depends on intact MTs.

The injection of colchicine into cnn embryos also enabled the centrioles to remain associated with the PCM (Fig. 3), suggesting that it is the MT-dependent rocketing of the centrioles that causes them to lose their connection to the PCM. The localized injection of colchicine into cnn embryos also enabled the centrioles to remain associated with the PCM, suggesting that it is the MT-dependent rocketing of the centrioles that causes them to lose their connection to the PCM.
that ultimately breaks the link between the centrioles and the PCM in cnn embryos. Intriguingly, however, the injection of colchicine into cnn embryos did not correct the positioning defect of the centrioles within the PCM; whereas the centrioles were usually (>90%) well centered within the PCM in colchicine-injected WT embryos (between 50 and 100 centrioles observed with each of the three different PCM markers; Fig. 3 and Video 6, available at http://www.jcb.org/cgi/content/full/jcb.200704081/DC1), they were very rarely centered within the PCM in colchicine-injected cnn embryos (<10%) and were usually positioned at the very edge of the PCM (>100 centrioles observed with each of the three different PCM markers; Fig. 3 and Video 6).

This last observation was unexpected, and we are unaware of any other perturbation to the centrosome that results in this very specific displacement of the centrioles from the center of the PCM. This observation may have important implications for understanding how Cnn functions to maintain the link between the centrioles and the PCM. One interesting possibility is that the MT-dependent centriole rocketing we observe in cnn embryos may be mechanistically related to the actin-dependent rocketing of certain pathogenic bacteria (Borisy and Svitkina, 2000; Higgs and Pollard, 2001). These bacteria are coated with proteins that initially stimulate the polymerization of an actin “cloud” symmetrically around the surface of the bacteria. If the actin surrounding the bacteria is structurally weak, it can “fracture”, allowing the bacteria to move to the edge of the actin cloud and rocketing to begin (van Oudenaarden and Theriot, 1999; van der Gucht et al., 2005). Thus, we propose that the primary function of Cnn may be to mechanically strengthen the PCM. In the presence of Cnn, the PCM is structurally strong and the centrioles can maintain their position at the center of the PCM; in the absence of Cnn, the PCM is weakened and the centrioles move to the edge of the PCM. This then initiates centriole rocketing, although the exact mechanism of this MT-dependent rocketing remains unclear.

**Centriole segregation is defective in cnn mutant somatic cells**

Maintaining the proper connection between the centrioles and the PCM is clearly crucial in syncytial embryos, as a lack of Cnn results in catastrophic failures in mitosis. In contrast, somatic cells that lack Cnn have few mitotic defects, and cnn mutant flies are viable (Megraw et al., 2001; Mahoney et al., 2006). To test whether Cnn was required to maintain the proper connection between the centrioles and the PCM in somatic cells, we treated third instar larval brain cells with colchicine to depolymerize the MTs and then fixed and stained them to examine the distribution of the centrioles and the PCM. We found that hardly any PCM was detectable around the centrioles in cnn brain cells that had not been treated with colchicine (unpublished data). In cnn cells treated with colchicine, however, considerable amounts of PCM accumulated around the centrioles, but, as in cnn embryos, the centrioles were displaced from the center of the PCM (Fig. S2, available at http://www.jcb.org/cgi/content/full/jcb.200704081/DC1).

To further investigate whether the centrioles in cnn somatic cells behaved in the same way as the centrioles in cnn embryos, we examined living third instar larval NBs expressing the centriole marker DSas-4–mRFP and GFP–α-tubulin. In WT NBs entering mitosis, the centrioles were always centered within astral MT arrays, and the centrioles remained tightly associated with the poles of the spindle throughout mitosis (Fig. 4 A). In contrast, the centrioles in cnn NBs were often not associated with prominent astral MTs and exhibited irregular movements throughout the cell during mitosis. As a consequence, they were often abnormally displaced from the poles of the mitotic spindles (Fig. 4 B). Nevertheless, we could transiently detect astral MTs associated with some of the “rocketing” centrioles in some cnn NBs (Fig. 4 C, arrows; see the next section). In fixed larval cnn NBs, the centrioles were often randomly positioned around the cell (Fig. 4 E), and we noticed that 20–30% of brain cells had either too few or too many centrioles (Fig. 4 F). Taken together, these findings suggest that the centriole behavior is similar in cnn embryos and somatic cells; while these defects do not lead to dramatic errors in somatic cell division, they do lead to errors in centriole segregation. These findings support the hypothesis that centrioles have evolved the ability to recruit PCM...
to ensure the equal partitioning of the centrioles during cell division, rather than to ensure the efficient assembly of the mitotic spindle (Pickett-Heaps, 1969; Rieder et al., 2001).

**Asymmetric cell divisions are only mildly perturbed in cnn mutant NBs**

The Cnn-related protein CDK5RAP2 has been implicated in human microcephaly (Bond et al., 2005), and several recent studies have shown that centrosomes exhibit an asymmetric behavior during the asymmetric divisions of male germline stem cells (GSCs) and larval neural stem cells (NBs) (Rebollo et al., 2007; Rusan and Peifer, 2007; Yamashita et al., 2007). During interphase in these cells, only one centrosome is initially associated with PCM and MTs, but fails to maintain their connection to them. The distribution of MTs (red), centrioles (D-PLP; green), and DNA (blue) in fixed WT and cnn mutant cells. In cnn mutant cells (E), the centrioles are more randomly distributed in the cell and are sometimes of unequal size (which may reflect the clustering of some centrioles). (F) Bar chart showing the number of centrioles present in WT and cnn mutant mitotic brain cells. Error bars represent SD. Bars, 5 μm.

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**Figure 4. Centriole segregation is abnormal in cnn mutant larval brain cells.** (A and B) Time series (min:s) of living WT and cnn mutant NBs expressing the centriole marker DSas-4–mRFP (arrows; pseudocolored green) and GFP–α-tubulin (pseudocolored red). (A) In WT cells, the centrioles are always located at the poles of the mitotic spindle. (B) In cnn NBs, the centrioles move erratically around the cell and no longer maintain their proper connection to the poles of the mitotic spindle. Note that one of the centrioles temporarily moves out of the focal plane (13:30) but reappears by the end of mitosis. (C) Another cnn NB expressing the same markers as in A and B (colors are inverted). Both centrioles are able to nucleate astral MTs but fail to maintain their connection to them. (D and E) The distribution of MTs (red), centrioles (D-PLP; green), and DNA (blue) in fixed WT and cnn mutant cells. In cnn mutant cells (E), the centrioles are more randomly distributed in the cell and are sometimes of unequal size (which may reflect the clustering of some centrioles). (F) Bar chart showing the number of centrioles present in WT and cnn mutant mitotic brain cells. Error bars represent SD. Bars, 5 μm.
second centrosome eventually associates with PCM and MTs, it localizes to the opposite side of the cell, thus ensuring that the forming mitotic spindle is correctly oriented relative to these positional cues.

This asymmetric centrosome behavior appears to be important in male GSCs, as the asymmetric division of these cells is dramatically perturbed in cnn mutants (Yamashita et al., 2003). Although cnn mutant NBs have defects in aligning their spindles with cortical determinants early in mitosis (Megraw et al., 2001), it is not clear that this ultimately leads to failures in asymmetric division: early mitotic spindle alignment defects are often corrected in these cells by the time the cells divide (Cai et al., 2001). To determine whether cnn mutant NBs ultimately divide asymmetrically, we analyzed living WT and cnn third instar larval NBs expressing only GFP–α-tubulin.

As reported previously (Rebollo et al., 2007; Rusan and Peifer, 2007), a single, anchored MTOC was usually visible in WT NBs before the entry into mitosis (not depicted). After nuclear envelope breakdown (NEB), however, both centrosomes nucleated prominent arrays of MTs, and spindle assembly occurred primarily by a centrosomal pathway (Fig. 5 A and Video 7, available at http://www.jcb.org/cgi/content/full/jcb.200704081/DC1). As expected, the cells divided asymmetrically to produce a large NB and a small ganglion mother cell (GMC). In most cnn NBs, no prominent MTOC was detectable before NEB, and spindle assembly occurred largely by an acentrosomal pathway (Fig. 5 B and Video 8). Nonetheless, ~95% of cnn NBs ultimately divided asymmetrically (n = 81; Fig. 5 B and Video 8), whereas ~4% divided symmetrically (Fig. 5 C and Video 9) and ~1% failed in cytokinesis (not depicted). Although this failure rate is modest, we believe it is considerably higher than in WT, as we observed only one symmetric division in >100 WT central brain NBs examined (unpublished data; Basto, R., and C.I. Dix, personal communication).

We previously showed that mutations in DSas-4, which encodes the Drosophila homologue of the human microcephaly protein CenpJ/CPAP (Bond et al., 2005), also lead to defects in the asymmetric divisions of larval NBs. The defects were much more severe in DSas-4 mutants, which completely lack centrioles/centrosomes (~15% of NBs divided symmetrically, whereas ~15% failed in cytokinesis; Basto et al., 2006). The much milder defects in asymmetric division that we observe in cnn NBs suggest that centrosomes are partially functional as MTOCs in cnn mutant somatic cells, consistent with our previous observations (Fig. 4 C and Fig. S2). Indeed, we frequently observed relatively well-focused astral MT arrays forming and disassembling in the

Figure 5. Asymmetric cell divisions are mildly perturbed in cnn mutant NBs. Time series (min:s) of MT behavior in living third instar larval NBs. [A] In a WT NB, the centrosomes nucleate prominent arrays of astral MTs before NEB (0:00), and the spindle is assembled primarily from these MTs. This cell divides asymmetrically (17:57) to produce a large NB and a small GMC (cell areas are outlined; see Video 7, available at http://www.jcb.org/cgi/content/full/jcb.200704081/DC1). [B] In this cnn mutant NB, astral MTs are undetectable, and the spindle appears to assemble around the chromatin; nevertheless, the cell divides asymmetrically (Video 8). [C] In this cnn mutant NB, some astral MTs are visible, but the cell ultimately divides symmetrically (Video 9). [D] In this cnn mutant NB, prominent astral MTs transiently form at one of the poles of the spindle (arrow), and a small, transient focus of MTs can be seen moving around in the cytoplasm (arrowheads; Video 10). Bar, 5 μm.
cytoplasm, and these were often transiently associated with the spindle poles in cnn NBs (Fig. 5 D, arrow; and Video 10, available at http://www.jcb.org/cgi/content/full/jcb.200704081/DC1). Taken together, our observations on cnn and DSas-4 mutant NBs reveal that, unlike the situation in male GSCs, the asymmetric behavior of the centrosomes is not essential for the accurate asymmetric division of larval NBs. Nevertheless, mutations in the Drosophila homologues of two of the three human centrosomal proteins implicated in microcephaly do lead to relatively subtle defects in NB divisions in flies. Drosophila cnn and DSas-4 mutants do not have small brains, suggesting that flies are able to compensate for defects in these divisions in a way that perhaps humans cannot.

Materials and methods

Fly stocks
COregon R or yw flies were used as the WT stock, and yw flies as the parental stock for the generation of all transgenic lines. The cnn\textsuperscript{H21} null allele has been described previously (Megraw et al., 1999; Vaizel-Ohayon and Schejter, 1999), and the cnn\textsuperscript{G62} allele, a pigggyBac insertion in the middle of the cnn gene (Exelixis stock no. I04547), was obtained from the Exelixis Stock Centre (Harvard Medical School, Boston, MA). In Western blotting experiments, embryos laid by females homozygous for this allele had no detectable Cnn protein.

GFP and mRFP fusion proteins
GFP fusions to the following proteins were used in this study: Aurora A–GFP (Lau, J., personal communication), GFF–D-TACCC (Lee et al., 2001), Grip5-S-GFP (Schnorrer et al., 2002), GFP–α-tubulin (Grieder et al., 2000), and DSas-4–GFP (Peel et al., 2007). We also generated fusions between α-tubulin (Grieder et al., 2000), α-Grip75-GFP (Schnorrer et al., 2002), GFP–α-tubulin, dividing asymmetrically (Video 7); a WT larval NB expressing GFP–α-tubulin, dividing asymmetrically (Video 8); a WT larval NB expressing GFP–α-tubulin, dividing symmetrically (Video 9); or Grip75-GFP and GFP–α-tubulin, dividing asymmetrically (Video 8); a WT larval NB expressing GFP–α-tubulin, dividing asymmetrically (Video 7); a cnn larval NB expressing GFP–α-tubulin, dividing asymmetrically (Video 8); a cnn larval NB expressing GFP–α-tubulin, dividing symmetrically (Video 9); a cnn larval NB expressing GFP–α-tubulin with prominent astral MTs, and a small focus of MTs moving around the cell (Video 10). Online supplemental material is available at http://www.jcb.org/cgi/content/full/jcb.200704081/DC1.

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