

Roles of Aurora Kinases in Mitosis and Tumorigenesis

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Abstract

Aurora kinases, which have been implicated in several vital events in mitosis, represent a protein kinase family highly conserved during evolution. The activity of Aurora kinases is delicately regulated, mainly by phosphorylation and degradation. Deregulation of Aurora kinase activity can result in mitotic abnormality and genetic instability, leading to defects in centrosome function, spindle assembly, chromosome alignment, and cytokinesis. Both the expression level and the kinase activity of Aurora kinases are found to be up-regulated in many human cancers, indicating that these kinases might serve as useful targets for the development of anticancer drugs. This review focuses on recent progress on the roles of Aurora kinases in mitosis and tumorigenesis. (Mol Cancer Res 2007;5(1):1–10)

Introduction

Aurora kinases represent a novel family of serine/threonine kinases crucial for cell cycle control. The first Aurora kinase was discovered in *Drosophila* (1). Because its mutations resulted in a failure of centrosome separation, leading to the formation of monopolar spindles, it was given the name “Aurora,” reminiscent of the North Pole. Since then, homologues of Aurora have been identified in different species. *Saccharomyces cerevisiae* has a single Aurora kinase: Ip11 (increases in ploidy 1; ref. 2). In *Caenorhabditis elegans* (3, 4), *Drosophila* (1, 5), and *Xenopus* (6, 7), there are two types of Aurora kinases: Aurora-A and Aurora-B. Mammals own at least three Aurora kinases: Aurora-A, Aurora-B, and Aurora-C (for nomenclature, see ref. 8).

Special interest in Aurora kinases has arisen since people discovered that defects in these kinases lead to severe mitotic abnormality. Silencing of Aurora-A leads to abnormal spindle

morphology in *C. elegans*, *Drosophila*, and human cells (1, 9, 10), whereas disruption of Aurora-B causes chromosome misalignment and cytokinesis failure in both *Drosophila* and HeLa cells (11, 12), indicating their multiple roles in centrosome function, chromatid separation, and cytokinesis. Little is known about Aurora-C until recent reports show that Aurora-C is also a chromosomal passenger protein, and that it binds directly to INCENP and survivin *in vitro* (13-15). Given the facts that Aurora-C-INCENP can phosphorylate endogenous histone H3 in mammalian cells, and that Aurora-C could rescue the Aurora-B-silenced multinucleation phenotype in human cells, Aurora-B and Aurora-C may be functionally overlapping (13-15). Here, we will refer primarily to Aurora-A and Aurora-B because the expression of Aurora-C is largely limited to the testes, and because there is a paucity of Aurora-C-related data.

Aurora kinases are overexpressed in a variety of tumor cell lines (16-18), suggesting that these kinases might play a role in tumorigenesis. In particular, Aurora-A can transform certain cell lines when overexpressed (17, 19, 20). Inhibitors of Aurora kinases are used in cultured cells and xenograft models to treat cancer, and an encouraging effect has been shown (21, 22).

In this article, we mainly review the roles of Aurora kinases in the regulation of mitotic progression and tumorigenesis. We will also discuss these kinases as potential targets for cancer diagnosis and therapy.

Aurora Kinases and Their Subcellular Distribution

Aurora kinases comprise mainly two domains: a regulatory domain in the NH₂ terminus and a catalytic domain in the COOH terminus. The regulatory domain is diverse largely, whereas the catalytic domain with a short segment of diverse COOH terminus shares >70% homology among Aurora-A, Aurora-B, and Aurora-C (Fig. 1A). There is a D-Box in the COOH terminus and an A-Box in the NH₂ terminus of Aurora kinases, which are responsible for degradation (23-26). Sequence analysis and point mutations revealed that phosphorylation at the threonine site within the catalytic domain is required for the kinase activity (27, 28).

Crystal structures of the Aurora-A and Aurora-B catalytic domain have been resolved recently (28-30). Like other serine/threonine protein kinases, Aurora kinases contain two lobes in their catalytic domain joined up by a hinge. The N lobe is responsible for positioning the ATP phosphate group through an α C helix, whereas the activation loop within the C lobe is able to harbor substrates (28, 31). Only when the two lobes arrive at a certain conformation can the Aurora kinases fulfill

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their kinase functions. Thus far, the NH₂-terminal domain has not yet been explored in the tertiary structure level.

Despite great similarities in sequences and structures, Aurora kinases are completely different in their subcellular distribution (Fig. 1B). Aurora-A localizes to the pericentriolar material from the end of S phase to the beginning of the next G₁ and spreads to the pole proximal ends of spindle microtubules during mitosis. In contrast, Aurora-B remains in the nucleus and moves to centromeres from prometaphase to metaphase. After anaphase begins, Aurora-B relocates gradually to the midzone and persists at the midbody until cytokinesis is completed. Moreover, Aurora-B undergoes different localizations along with at least three other partners: INCENP, survivin, and Borealin. They form a tight complex within the cell during mitosis and are named “chromosomal passengers” as they move precisely from site to site at specific times.

Aurora Kinases and Mitotic Control

Aurora-A and Aurora-B exhibit divergent functions in mitotic control, corresponding to different subcellular distribution of the two kinases. Aurora-A is mainly involved in

centrosome function, mitotic entry, and spindle assembly, whereas Aurora-B participates in chromatin modification, microtubule-kinetochore attachment, spindle checkpoint, and cytokinesis. Along with these two kinases, different partners and substrates take part in these processes.

Aurora-A Regulates Mitotic Spindle Assembly

The enrichment of Aurora-A either to the centrosome or microtubule compartment suggests that Aurora-A may play dual roles in mitotic spindle assembly (Fig. 2).

In G₂ phase, Aurora-A first localizes to pericentriolar material and is activated by the LIM protein Ajuba (32), which is required for centrosome maturation. Centrosome maturation takes place every cell cycle, referring to the recruitment of several pericentriolar material proteins that enhance microtubule nucleation ability in the late G₂ phase, such as γ -tubulin and some coiled-coil proteins (33). Depletion of Aurora-A decreases centrosomal γ -tubulin intensity as well as two other pericentriolar material components in *C. elegans* embryos (9). It has been corroborated in *Drosophila* and mammalian cells that Aurora-A is required to localize centrosomal protein

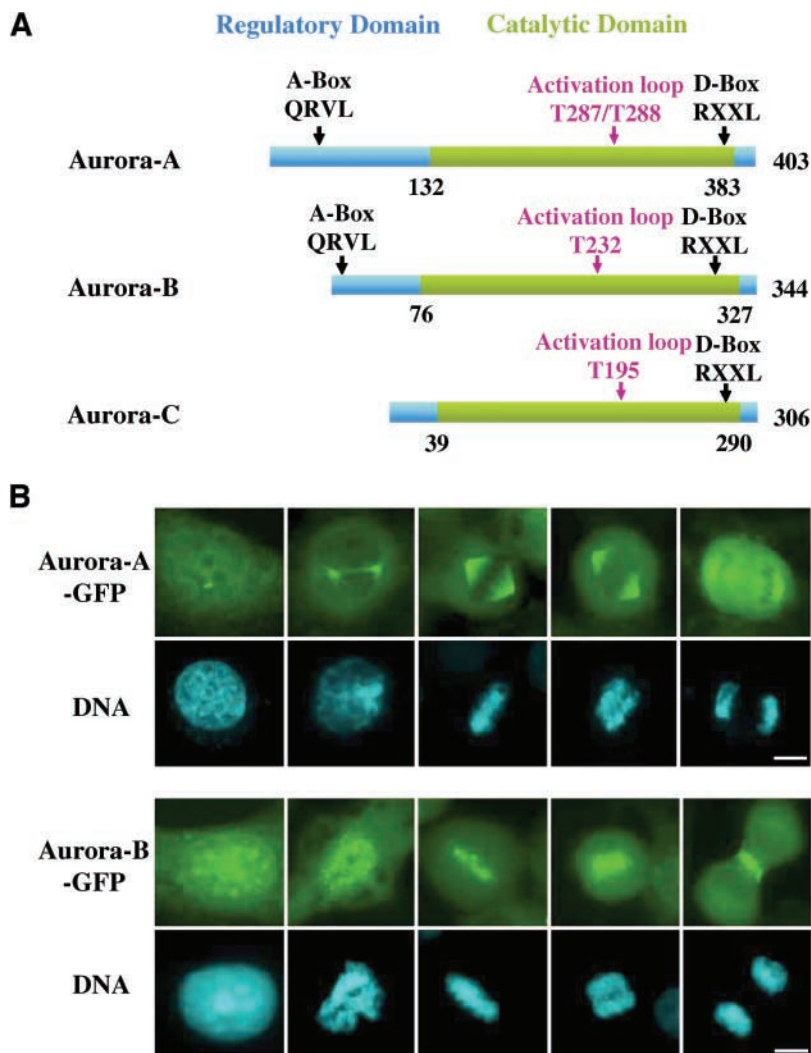
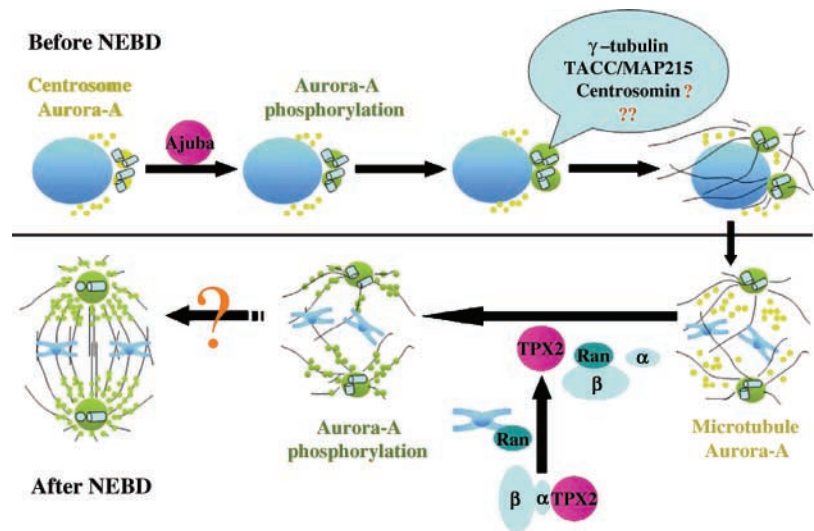


Figure 1. Human Aurora kinase structure and their subcellular distribution during mitosis. **A.** Aurora kinases contain mainly two domains: the NH₂-terminal regulatory domain (blue) and the COOH-terminal catalytic domain (green). The three homologues Aurora-A, Aurora-B, and Aurora-C share great homology in the catalytic domain yet differ in the NH₂-terminal domain and a small sequence in the COOH terminus (blue). Crucial structures (arrows). Phosphorylation at threonine within the activation loop is necessary for kinase activity (red). Besides, two boxes are identified as the recognition sites of APC/C^{dh1} and promoter of degradation (black): destruction box (D-Box) and D-Box-activating Box (DAD/A-Box), respectively. These features have been confirmed by experiments in both Aurora-A and Aurora-B; yet, the structure of Aurora-C is deduced by sequence alignment and seems to lack the A-Box. **B.** Aurora-A and Aurora-B are distinct in subcellular distribution during mitosis. By G₂ phase, Aurora-A localizes to pericentriolar material and persists throughout cell cycle. Additionally, it spreads to the minus ends of the mitotic spindle microtubules and midzone microtubules during mitosis. Diversely, Aurora-B and its “passenger” partners remain a part of centromeres from prometaphase to metaphase. After chromatids begin to separate, they relocate to midzone and persist at the midbody until cytokinesis is completed. These photographs were prepared by transfecting HeLa cells cultured on coverslips with Aurora-A-GFP and Aurora-B-GFP, respectively. After fixing with methanol and acetone (1:1), coverslips were stained with 4',6-diamidino-2-phenylindole for DNA and mounted. Cells were viewed under an Olympus IX71 immunofluorescence microscope, and photographs were taken with SPOT cool CCD and SPOT image software. Bar, 5 μ m.

Figure 2. Aurora-A functions in spindle assembly. Two pools of Aurora-A exist within the cell: the centrosome Aurora-A and the microtubule Aurora-A. Before nuclear envelope breakdown (NEBD), Aurora-A localizes to the centrosome, where it is activated by Ajuba. Active Aurora-A further recruits γ -tubulin, TACC/MAP215 complex, centrosomin, and other centrosomal proteins to promote centrosome maturation and microtubule nucleation ability. Distinctively, the microtubule Aurora-A is diffused into cytoplasm and remains inactive. Once the nuclear envelope breaks down, this pool of Aurora-A is activated by the Ran pathway. During this process, high concentration of RCC1 near chromosomes transforms Ran-GDP into a GTP-bound state, which later binds to importin- β and releases TPX2. TPX2 not only activates Aurora-A but also localizes it to the microtubules, where Aurora-A exerts its functions in spindle assembly. Inactive form (yellow) and active form (green) of Aurora-A.



centrosomin, which could bind γ -tubulin and other centrosomal components (34, 35). Moreover, Aurora-A is necessary to recruit D-TACC/maskin to the centrosome and phosphorylates D-TACC/maskin at the centrosome in *Drosophila* and *Xenopus* (36-38). D-TACC/maskin forms a complex with Msps/XMAP215 and stabilizes microtubules around the centrosome by antagonizing the depolymerization activity of MCAK (37, 39). Therefore, it is convincing that Aurora-A facilitates centrosome maturation in microtubule nucleation ability by recruiting and/or phosphorylating centrosomal components, sequentially contributing to mitotic spindle assembly.

The second role of Aurora-A in spindle assembly is exerted when it localizes to the pole proximal ends of microtubules after nuclear envelope breakdown, prevailingly considered as a part of the Ran-spindle assembly pathway. Ran is a small GTPase and has been implicated in multiple mitotic events. During spindle assembly, high concentration of RCC1 near the chromosomal region transforms Ran-GDP into a GTP-bound state, which later releases the spindle assembly factors, such as TPX2 and NuMA, by inhibiting importin- α/β (40). The Ran-spindle assembly pathway was explored more extensively after the relation between TPX2 and Aurora-A was uncovered. The NH₂ terminus of TPX2 directly interacts with the COOH terminus of Aurora-A (41), triggering conformational changes in the activation segment of the kinase, thus not only stimulating the autophosphorylation but also burying the phosphothreonine site from protein phosphatase 1 dephosphorylation (28). TPX2 is also required for targeting Aurora-A to the spindle (41, 42). The interaction between Aurora-A and TPX2 undergoes the regulation of Ran-GTP gradient (42). Recently, profound evidence was shown that Aurora-A-coated magnetic beads could function as MTOCs in the presence of Ran-GTP in *Xenopus* egg extracts and induce bipolar spindle formation without centrosomes and chromatin, confirming the significance of Aurora-A in centrosome function and spindle assembly (43). It might be a hint that Ran directs spindle assembly by transforming its gradient of active form to the activity of protein kinases, such as Aurora-A, hence passing the commands on to the yet unknown downstream substrates.

Therefore, identifying the substrates of Aurora-A will be an exciting task in investigating the mechanism of spindle assembly.

Interestingly, three newly published articles identified HURP as a Ran-importin- β -regulated protein involved in spindle assembly (44-46). HURP mainly concentrates at the chromosome proximal ends of mitotic spindle (45, 46), where it stabilizes kinetochore fibres and promises a normal interkinetochore tension and efficient kinetochore capture (45, 46). Such HURP distribution exhibits a Ran-GTP dose-dependent characteristic and is damaged by excessive importin- β or Ran-GDP (44, 45). It has been reported that Aurora-A phosphorylates and stabilizes HURP *in vitro* and *in vivo* during mitosis (47). Given the reverse gradient of their distribution on microtubules, it would be really important to investigate how Aurora-A and HURP correspond to the signal of the Ran pathway.

Aurora-A Regulates Centrosome Separation

Duplicated centriole pairs separate at the G₂-M transition, marching to the opposite poles of the cell for proper establishment of bipolar spindle. There is evidence that centrosome separation requires functional Aurora-A. RNA interference or microinjection of Aurora-A antibody in HeLa cells could prevent centrosome separation (10). In *C. elegans* embryos, Aurora-A knockdown by RNA interference could interrupt centrosome separation and spindle assembly (9). In *Xenopus*, a dominant-negative mutation of Aurora-A results in monopolar spindle (6, 48), a phenomenon similar to the inhibition of a kinesin-related protein XIEg5 (48). Because XIEg5 is phosphorylated by *Xenopus* Aurora-A both *in vivo* and *in vitro* (48), it might be possible that Aurora-A regulates centrosome separation by phosphorylating the kinesin-related proteins.

Aurora-A Regulates G₂-M Transition

Apart from the spindle assembly and centrosome separation, Aurora-A contributes to transition from G₂ to M phase.

Suppression of Aurora-A by RNA interference results in G₂-M arrest of HeLa cells and promotes apoptosis (49). Phosphorylation of CDC25B at the centrosome by Aurora-A was discovered in HeLa and U2OS cell lines, and this phosphorylation is an important step to relocalize cyclin B1 to the nucleus and activate cyclin-dependent kinase 1 for the cell to enter mitosis (50). It was also found that ectopic expression of Aurora-A could bypass the G₂-M checkpoint activated by DNA damage (50).

Aurora-B Regulates Chromatin Protein Modification

It has been found that Aurora-B phosphorylates histone H3 at Ser¹⁰ and Ser²⁸ (51, 52) as well as its variant CENP-A at Ser⁷ (53, 54) in mitosis. H3-S10 phosphorylation is now widely used in Aurora-B kinase assay; yet, the function remains largely unknown. In *Tetrahymena*, H3-S10 phosphorylation is required for chromosome condensation (55, 56); however, the connection between these two events is still elusive in mammalian cells. Moreover, a recent experiment showed that H3-S10 phosphorylation by Aurora-B allows the routine disassociation of HP1 from heterochromatin (57, 58), but the biological effect of HP1 release in mitosis is still unclear. Interestingly, Aurora-A also phosphorylates CENP-A (54). Phosphorylation of CENP-A by Aurora-A at Ser⁷ in prophase is required for Aurora-B concentration to inner centromeres in prometaphase. Maintenance of later CENP-A phosphorylation state depends on Aurora-B activity and is required for proper microtubule-kinetochore attachment (54). It would be meaningful to explore how Aurora-A and Aurora-B cooperate in understanding the subtle regulation of mitosis.

Aurora-B Regulates Chromatid Separation

Accurate separation of chromatids requires attachment of each kinetochore to microtubules from the opposite poles. Two

mechanisms in cells are raised to regulate this process: one is the correction of error attachment, and the other is the spindle checkpoint. Because Aurora-B inhibition causes a higher frequency of syntelic and/or merotelic attachments in cells during prometaphase and drives these cells to enter anaphase with no arrest and misaligned chromosomes (12, 22), it has long been proposed that Aurora-B plays a crucial role in both pathways.

Recently, two laboratories have discovered that Aurora-B phosphorylates centromeric MCAK to inhibit its microtubule depolymerization activity during the mitotic spindle assembly (59, 60). They found that, in mitosis, if microtubule-kinetochore attachment is in a bipolar fashion, Aurora-B may phosphorylate MCAK to keep the kinetochore microtubules in a more stable form. Otherwise, the phosphorylation of MCAK by Aurora-B is abolished, and the kinetochore microtubules are depolymerized to allow other microtubules to catch the unattached kinetochores (Fig. 3A). Phosphorylated and unphosphorylated MCAK proteins exhibit slight difference in localization, with the former closer to the inner centromere where Aurora-B is enriched and the latter closer to inner kinetochore bound of protein phosphatase 1 (59, 61, 62). It is conceivable that the dynamics of phosphorylation/dephosphorylation modification of MCAK protein might be the way that Aurora-B and protein phosphatase regulate the kinetochore-microtubule connection.

The other surveillance mechanism is the spindle checkpoint, which checks whether unattached kinetochores exist. The checkpoint proteins are located on unattached kinetochores and inhibit the APC/C activity to prevent cells from entering anaphase. Aurora-B is involved in the recruitment of checkpoint proteins to kinetochores (Fig. 3B). Cytostatic factor extracts depleted of Aurora-B show diminishment of Mps1, Bub1, CENP-E, Bub3, Mad1, and Mad2 to kinetochores (63). When cells treated with ZM447439, an inhibitor of Aurora-B, or depleted of Bub1 were done with checkpoint induction,

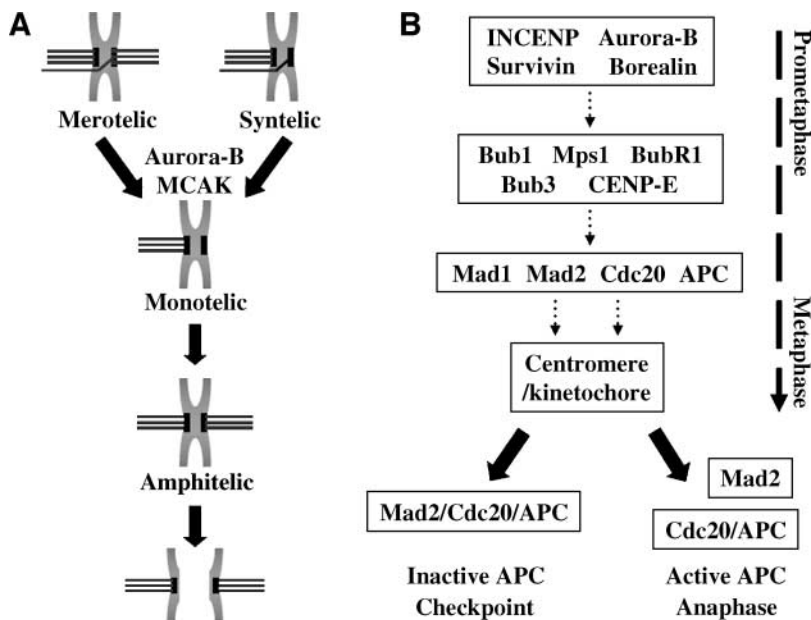


Figure 3. Aurora-B regulates chromatid separation. **A.** Aurora-B guarantees proper attachment between microtubules and kinetochores. After nuclear envelope breakdown, microtubules from opposite poles catch the sister kinetochores and form bipolar spindle, which later ensures accurate chromatid separation. During this process, error attachment, such as syntelic or merotelic, happens quite often. This error can be corrected through the monotelic form with the help of Aurora-B and MCAK before cells enter anaphase. **B.** Spindle checkpoint is activated when unattached kinetochores exist. It requires a large scale of checkpoint protein machinery, including Bub1-3, Mad1, Mad2, BubR1, Mps1, CENP-E, and Aurora-B, complexed with the other passenger members. These spindle checkpoint proteins are recruited to centromere/kinetochore as a certain cascade in the figure, with Aurora-B complex mostly upstream, and Mad1/Mad2 mostly downstream. Mad2 can directly interact with APC/C/Cdc20 and inhibit the activation of APC/C; thus, cell cycle is suspended in metaphase. In particular, Aurora-B complex is responsible for assembling all the other checkpoint proteins to centromere/kinetochore, therefore promising a functional checkpoint.

Bub1 and Aurora-B function in two different signaling pathways and converge on the mitotic checkpoint complex, which includes BubR1, Bub3, Mad2, and Cdc20 (64). However, whether Aurora-B is directly involved in checkpoint activation, or whether it just guarantees recruitment of checkpoint proteins, remains a mystery. Experiments using temperature-sensitive kinetochore mutants in budding yeast revealed that when kinetochores undergo tension defects, Aurora-B creates unattached kinetochores to activate the spindle checkpoint (65), but in higher eukaryotes, this has not yet been proven.

Aurora-B Regulates Cytokinesis

Aurora-B plays an essential role in cytokinesis. Depletion of Aurora-B produces polyploidy due to a failure in cytokinesis in *C. elegans* embryos and *Drosophila* S2 cells (4, 66). Although the mechanism has not yet been elucidated, several substrates of Aurora-B were identified, including the type III intermediate filament desmin and vimentin (67, 68), midbody component ZEN-4/MKLP1 (69, 70), and other proteins like TACC1 (71) and MgcRacGAP (72). Aurora-B and Rho, a prominent regulator of cytokinesis, share certain substrates but exert phosphorylation independently, suggesting that Aurora-B and Rho might coordinate in cytokinesis control (73). Moreover, Aurora-B activates Rho by converting MgcRacGAP to a RhoGAP during cytokinesis (72), indicating that Aurora-B is multifunctional in cytokinesis regulation.

Functional Regulation of Aurora Kinases

The activity of Aurora kinases undergoes strict regulation during mitosis. Aurora-A reaches the maximum activity at the G₂-M transition, whereas the activity of Aurora-B persists from metaphase to the end of mitosis (74). This mechanism of regulation turns out to be a complicated process of phosphorylation and degradation.

Aurora Protein Phosphorylation

Different from most kinases within the cell, Aurora kinases are activated through autophosphorylation at the activation loop (29).

Aurora-A is activated mainly by Ajuba (32) and TPX2 (42) as well as protein phosphatase inhibitor-2 (75), the focal scaffolding protein HEF1 (76), and a newly identified Bora protein (77). Phosphorylated Aurora-A is dephosphorylated by protein phosphatase 1 (78). Up to now, TPX2 obtains the best understanding as an Aurora-A activator. In the absence of TPX2, the Aurora-A activation site is exposed to protein phosphatase 1 and is dephosphorylated in a crucial threonine; after binding to TPX2, the activation segment of Aurora-A rotates so that the phosphothreonine is buried inside and protected from protein phosphatase 1 (28).

A recent report raised a new question in screening for TPX2 homologue in *C. elegans*. The report discovered that a protein named TPXL-1 has homology with the NH₂-terminal domain of TPX2 (79). Surprisingly, although TPXL-1 could bind to and activate Aurora-A, it has neither a NLS signal nor the ability of chromatin-dependent microtubule nucleation (79), which have been shown to be the basic characteristic of TPX2. Thus, it has

been thought that TPXL-1 is not a true functional orthologue of TPX2 in *C. elegans* (80), and who will be the real activator of Aurora-A?

Less is investigated of Aurora-B regulators. Prevailing view believes that Aurora-B is regulated by other members of the passenger protein complex, especially activated by INCENP (81, 82). Crystal structure analysis showed that INCENP forms a crown around the N lobe of Aurora-B (30). Different from Aurora-A/TPX2 complex, INCENP induces the active conformation of the T loop allosterically. INCENP activates Aurora-B in a two-step process: it partially activates the kinase at the first step, with the N lobe and C lobe of Aurora-B in an open position; then, full activation of the kinase carries on after INCENP phosphorylation in a conserved TSS motif near the COOH terminus, and the two lobes of Aurora-B close (30). Up to the present, whether survivin bound to Aurora-B stimulates Aurora-B kinase activity remains contradictory (81, 82). Recombinant survivin can enhance an Aurora-B IP kinase assay in *Xenopus* mitotic extracts for >10-fold, and overexpression of survivin in HEK293 cells also elevates the Aurora-B kinase activity (81, 83). Nevertheless, another *in vitro* kinase assay using recombinant proteins showed that survivin does not detectably influence the activity of Aurora-B kinase (82).

Aurora Protein Degradation

Aurora kinases are barely detected after cells exit mitosis and enter G₁ phase. Destruction of both Aurora-A and Aurora-B is mediated by APC/C^{Cdh1} (23, 25, 84). Several domains within their sequences have been identified for degradation, including KEN-box, D-box, and A-Box (23, 24, 26). Nevertheless, they are not all necessary for the degradation of both Aurora-A and Aurora-B. Aurora-A destruction requires D-box and A-box but not KEN-box (26), whereas Aurora-B degradation needs intact KEN-box and A-box (23). This difference might partially explain the distinct temporal regulation of their kinase activity.

Discrimination between Aurora-A and Aurora-B

It is worth pointing out that Aurora-A and Aurora-B share little regulators or substrates despite their high similarity in sequence. How are they discriminated, for example, by TPX2? Using structure-based mutation, Byliss and Eyer found that a single amino acid mutation in Aurora-A to the homologue site of Aurora-B abolishes TPX2 recognition and vice versa (31, 85). It provides us a view that Aurora kinases experience delicate regulation in regulating mitosis events.

Aurora Kinases and Tumorigenesis

Aurora kinases are overexpressed in a wide range of human cancers. Human Aurora-A was first isolated as the product of gene *BTA*K (breast tumor amplified kinase, also named *STK15*) on chromosome 20q13, a region that is commonly amplified in primary breast tumors, colorectal cancers, and other cancer cell lines, including breast, ovarian, colon, prostate, neuroblastoma, and cervical cell lines (17, 19, 86). More strikingly, overexpression of Aurora-A transforms NIH 3T3 cells and Rat1 fibroblasts *in vitro*; when these cells were injected into nude mice, they grew into tumors (17, 19, 20). However, whether

Aurora-A is a potential oncogene remains controversial because no more cell lines were found to be transformed by overexpression of Aurora-A, and overexpression of Aurora-A in mouse model did not result in malignant tumor after a long latency (87). These data suggest that Aurora-A might be a promoting factor for tumorigenesis, and other factors are also needed in cell transformation process. For Aurora-B, the case is even more complicated. Aurora-B is also expressed at high level in primary human colorectal cancers and other tumor cell lines (18). Overexpression of Aurora-B results in multinucleation and polyploidy in human cells (16, 88). However, down-regulation or overexpression of an inactive form of Aurora-B yields the same polyploidization phenomenon. How Aurora kinases are involved in tumorigenesis would be discussed further below (Fig. 4).

Aurora Kinases in Centrosome Amplification and Aneuploidy

Overexpression of Aurora-A causes centrosome amplification both in cell cultures and in rat mammary model (89-91). This kind of centrosome amplification seems not due to centrosome duplication but as a result of cytokinesis failure and consequent multinucleation (89). Up until now, no evidence has shown that Aurora-A functions in cytokinesis directly, and it would be more likely that Aurora-A causes cytokinesis failure in an indirect way, possibly by affecting Aurora-B or other proteins that directly regulate cytokinesis. Aurora-A-induced

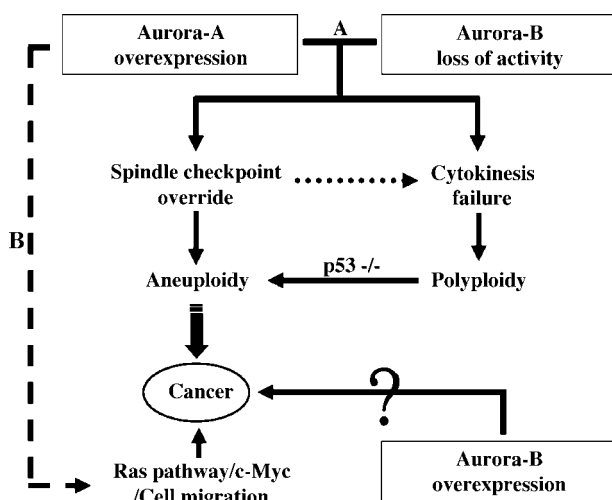


Figure 4. Aurora kinases and tumorigenesis. Up-regulation of Aurora kinases is related to a wide range of human cancers possibly due to their roles in mitosis control (A) and/or other pathways (B). Aurora-A overexpression or Aurora-B function disruption may override spindle checkpoint; thus, the cell divides with unequal genetic material and turns out to be aneuploidy. Besides, Aurora-A overexpression or Aurora-B function disruption may also lead to cytokinesis failure directly or indirectly, resulting in polyploidy. Under a second circumstance, if the cell loses its p53 and is unable to prevent itself from carrying on the next round of DNA replication, it may go to mitosis and also end up with aneuploidy, which is prevalently considered associating with cancer. Apart from the mitosis aberrance, Aurora-A also participates in the Ras/Raf/MEK/ERK/MAP kinase pathway, induces telomerase activity, and enhances collagen I-induced cell migration, which may also contribute to tumorigenesis. Aurora-B overexpression is found in some cancer cells too, but the mechanism is still poorly understood.

polyploid cells would be arrested by a “G₁ phase post-mitotic checkpoint” dependent on the p53-Rb pathway, and most of the cells would die through apoptosis. However, when these cells unfortunately lose p53 functions as in p53^{-/-} cells, they could not detect the hyperploidy and go on DNA replication and cell division, which might cause aneuploidy and abnormal centrosome number (89, 92).

Overexpression of Aurora-B also leads to centrosome amplification and increased ploidy, and the absence of p53 exacerbates this phenotype (88, 89). Nevertheless, Aurora-B-induced centrosome amplification is possibly due to other pathways. It has been reported that Aurora-B overexpression induces chromosomes lagging in metaphase, chromosome segregation error, and errors in cytokinesis, and thus may play a role in carcinogenesis (93).

Aurora Kinases with Spindle Checkpoint Defect and Chromosome Instability

Cells overexpressing Aurora-A override the mitotic spindle checkpoint and enter anaphase despite abnormal spindle formation (91). Interestingly, the checkpoint protein Mad2 remains at the kinetochores from prometaphase to anaphase, suggesting a persistently activated spindle checkpoint (91). Therefore, it might be possible that Aurora-A disrupts the interaction between Mad2 and cdc20 or prematurely activates APC/C proteolytic functions. It has been found that, when Aurora-A overexpression overrides the spindle checkpoint triggered by nocodazole, a microtubule destabilizer, BubR1 is significantly reduced, and a subunit of APC/C cdc27 could not be phosphorylated (94).

Depletion of Aurora-B or overexpression of an inactive form in cells would also compromise the spindle checkpoint because the activity of Aurora-B is required for checkpoint protein recruitment. Because cytokinesis would also fail without Aurora-B activity, it makes a good explanation why down-regulation of Aurora-B generates increased ploidy.

Aurora Kinases in Tumor Suppressor Gene Dysfunction and Cell Viability

Aurora-A interacts with several tumor suppressor gene products, including p53 (92, 95, 96), BRCA1 (97), NM23-H1 (98), and Chfr (99), and it might be a powerful way to promote cell viability and tumorigenesis. Thus far, the interaction between Aurora-A and p53 has been well investigated. On one hand, p53 suppresses Aurora-A-induced centrosome amplification and cellular transformation (100), whereas on the other hand, Aurora-A phosphorylates p53 and thus inhibits p53 activity and promotes degradation of this protein. Two Aurora-A phosphorylation sites have been identified in p53. By phosphorylating Ser²¹⁵, Aurora-A abrogates the DNA-binding and transactivation activity of p53 and subsequently inhibits downstream target genes of p53, such as p21 and PTEN (96). Phosphorylation of Ser³¹⁵ will enhance the affinity of p53 with Mdm2, which promotes ubiquitination and degradation of the p53 protein (95). Besides, Aurora-A directly binds to BRCA1 and phosphorylates it at Ser³⁰⁸, and abortion of this phosphorylation process can decrease the number of cells in M phase in mouse embryo fibroblasts (97). In addition, Aurora-A

is regulated by Chfr, a mitotic checkpoint protein and tumor suppressor. Chfr interacts with and ubiquitinates Aurora-A both *in vitro* and *in vivo* (99). Taken together, Aurora-A and tumor suppressor gene products are antagonistic in cell viability control. The balance of quantity and activity between Aurora-A and tumor suppressor gene products might be important to maintain the normal growth rate of cells.

Aurora Kinases in Other Signaling Pathways and Tumorigenesis

Recent studies found that Aurora-A is a downstream target of mitogen-activated protein kinase 1/ER2 in pancreatic cancer (101). In human carcinogenesis, the Ras/Raf/MEK/ERK/MAP kinase pathway would be enhanced, and the cell response to growth signals is known to increase (102). Therefore, Aurora-A overexpression might drive cells into a faster growing state.

In addition, Aurora-A induces telomerase activity and human telomerase reverse transcriptase by up-regulation of c-Myc (103). Because increase of telomerase activity is frequently seen in many cancer cells and would elongate cell survival time, Aurora-A might promise cell a longer life.

Furthermore, both Aurora-A and Aurora-B promote inappropriate cellular mobility (23, 104), which underlies invasion and metastasis of tumor cells (105). Aurora-A enhances collagen I-induced cell migration and anchorage-independent growth in Aurora-A-stable cell line by activating RalA (104). In the case of Aurora-B, overexpression or nondegradation mutants could promote anchorage-independent growth in soft agar (23). However, the molecular mechanism has not yet been elucidated.

Aurora Kinases, Tumor Diagnosis, and Therapy

Cancers vary greatly in their cause, symptoms, response to treatment, and possibility of cure, which cause difficulty in their diagnosis and therapy. Considering that Aurora kinases play a critical role in tumorigenesis, it might be of great importance to evaluate Aurora kinases in cancer detection and therapy.

Aurora Kinases in Tumor Detection and Prognosis

Elevated expression of Aurora-A has been detected in >50% of colorectal, ovarian, and gastric tumors and in 94% of invasive duct adenocarcinomas of the breast (21). Could Aurora-A serve as a clinical tumor prognosis marker? Microarray-based screening for molecular markers in medulloblastoma revealed positive staining for Aurora-A and identified it as an independent prognostic factor for overall survival (106). However, experiments comparing the level of Aurora-A expression in human breast tumor specimens with clinical variables revealed no association between Aurora-A staining and tumor size, lymph node status, or hormone receptor status (107).

Despite the above debate, studies of the polymorphism of Aurora-A have proven that Aurora-A is a candidate low-penetrance tumor-susceptibility gene in mouse and human (108), raising the possibility that it might be useful as a caution of predisposition to cancer. Two functional coding single nucleotide polymorphisms as 91T>A and 169G>A are

associated with occurrence of esophageal squamous cell carcinoma and increase the risk of esophageal cancer and gastric cancer (109-111). More clinical evidence is needed to answer if the genotype of Aurora-A would be involved in determining "cancer susceptibility."

Aurora Kinase Inhibitors in Cancer Therapy

Cancers are characterized by the unrestrained growth of cells. Therefore, modulation of abnormal cell cycle regulation would be a valuable therapeutic strategy to many tumor types. RNA interference targeting Aurora-A suppresses tumor growth and enhances the sensitivity to chemotherapy and UV irradiation-induced apoptosis in human cells (112, 113), showing its potential as a target for cancer therapy.

Thus far, several inhibitors of Aurora kinases have been reported (for review, see refs. 114, 115). One of them, VX-680, was designed against the ATP-binding site of Aurora kinases and was proven a high potent, selective, and reversible inhibitor. It greatly inhibits tumor growth in three xenograft models *in vivo*, including leukemia and colon and pancreatic tumors (21). This molecule ensures the possibility to use Aurora kinases as a target for cancer therapy. Other inhibitors of Aurora kinases have been analyzed, such as ZM447439 (22) and Hesperadin (12). Although it is not clear whether Hesperadin would cause tumor cell death, ZM447439 has shown its ability. In colony formation assay, ZM447439 is more toxic to proliferating cells than nondividing cells (22), indicating that it might also be a selective drug to kill tumor cells. These inhibitors provide us a powerful tool to explore the relationship among molecular mechanisms, clinical symptom, and disease therapy.

Perspectives

The Aurora kinase family provides a new concept to understand the mitosis process, tumorigenesis, and the possible relationship between them. It is known that cyclin-dependent kinases provide a regulatory system of the cell cycle. They require cyclins as binding subunits to achieve their kinase activity and affect downstream substrates. Likewise, Aurora kinases also bind to their partners, such as TPX2 and INCENP, to maintain kinase activity. Interestingly, Aurora-A and Aurora-B show much difference in subcellular distribution and carry out divergent functions that are tightly related to their distribution, even if they share >70% homology in their catalytic domain. It might be intriguing to establish and compare the regulation networks of different Aurora kinases. At the mean time, it might be meaningful to investigate the relationship between the cyclin-dependent kinase regulatory system and the Aurora-like regulatory systems.

It is striking to note that deregulation of a single mitotic regulator might lead to huge risk of tumorigenesis. Of particular interest, Aurora kinases are shown to be candidate targets to inhibit tumor cell growth. We believe that uncovering the molecular function of Aurora kinases will bring great rewards in understanding cell cycle control and provide new strategies for drug design in cancer therapy.

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