acceleration which the water would have had if the body was not present. It is proportional to the wave height.

Budal realized that if we fit a spinning sleeve round a submerged horizontal cylinder we will be able to produce a lift as predicted by Magnus (K. Budal & P. M. Lillebeken *IUTAM Symp. Hydrodynamics Ocean Wave Energy* (eds D. V. Evans & A. F. de O. Falcao) 205–215 (Springer, Berlin, 1985)). This lift will be, by definition, 90° ahead of the velocity field and so will be parallel or anti-parallel to the acceleration field. It follows that the lift will add to or, by changing spin direction, subtract from or even reverse the wave loads. Budal's work with small scale models has been

replicated. It is not yet known whether the effect will scale up as well as the Flettner rotor did. If it does, the implications for wave energy are profound. A 5-metre Evans' cylinder could behave like a 15-metre one but could progressively shed its wave loading when things got uncomfortable. All that it would need would be a thin rotating outer sleeve which would use about 1 per cent of the output power to drive it. Scaling-up the Budal effect may very well be related to the vortex shedding which makes the Skews' polygons rotate. □

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CELL BIOLOGY

ABG of microtubule assembly

Caroline E. Alfa and Jeremy S. Hyams

RESOLUTION of the long-standing uncertainty over how the polar assembly of microtubules in living cells is organized has come a step nearer with the publication of two papers in *Cell*^{1,2}. Zheng *et al.*¹ and Stearns *et al.*² have discovered that the newest member of the tubulin superfamily, γ -tubulin, is specifically localized to the centrosome, the animal cell's microtubule organizing centre, and is thereby centrally implicated in the establishment of polarity.

In the relatively short period since its discovery³ γ -tubulin has intrigued microtubule researchers, who for 20 years previously had been content in the knowledge that microtubules were composed of α/β tubulin dimers^{4,5}. Although it has been shown through molecular techniques that the genomes of most organisms contain several α - and β -tubulin genes (vertebrates, for instance, contain six or seven of each⁶), the appearance of a completely new addition to the family was a great surprise. The discovery of γ -tubulin derived, not like that of α and β from classical grind-and-find biochemistry, but from a painstaking combination of classical and molecular genetics in that much underrated organism, the bread mould *Aspergillus nidulans*.

The gene *mipA* (for microtubule-interacting protein) was isolated as an allele-specific, extragenic suppressor of *benA33*, a heat-sensitive β -tubulin mutant of *Aspergillus* that at the restrictive temperature is defective in both mitosis and the movement of nuclei along hyphae (another microtubule-dependent process)⁷. When cloned and sequenced, *mipA* was found to encode a protein of 454 amino acids that is distinct from the α - and β -tubulins but about as similar to each as they are to one

another (just over 30 per cent similarity in amino acid sequence)³. Disruption of *mipA* resulted in spores that could germinate and undergo DNA synthesis, but that could not carry out nuclear division and therefore died⁸. Most surprisingly, an antibody to γ -tubulin failed to stain microtubules by indirect immunofluorescence microscopy but reacted specifically with the spindle pole bodies, the microtubule organizing centres of this and other fungi (see our previous News and Views article⁹).

These initial studies did not however address the key question — is γ -tubulin merely a curiosity of the *Aspergillus* microtubule cytoskeleton, or is it of more general significance? This issue has been unequivocally resolved in the *Cell* papers^{1,2} and another now in press¹⁰. Extending their own earlier studies, Zheng *et al.*¹ have now isolated γ -tubulin genes from *Drosophila* and *Homo sapiens*. The sequences of both are very similar to that of the original *Aspergillus* gene, meaning that γ -tubulin is likely to be a highly conserved protein. Moreover, antibodies to the fungal protein stained the centrosomes of both insect and human cultured cell lines, suggesting that γ -tubulin might be a ubiquitous component of microtubule organizing centres.

Centrosomes consist of two distinct elements, the centrioles and their surrounding shell of ill-defined pericentriolar material. Microtubules seed from the latter, and using immunogold electron microscopy, Stearns *et al.*² have demonstrated that it is this material with which γ -tubulin is associated. These workers have also greatly extended the survey of γ -tubulin gene distribution by isolating homologues from *Xenopus* and fission yeast. Again, both are closely related to

mipA. Moreover the authors report the isolation of partial sequences from a higher plant, an alga and a budding yeast. The fission yeast gene has also been isolated by Horio *et al.*¹⁰ who further showed that, as in *Aspergillus*, γ -tubulin antibodies stained the spindle pole bodies and also a second pair of microtubule organizing centres that appear transiently at the equator of late mitotic cells in this yeast.

How do these observations bear on microtubule assembly? As a consequence of their formation from aligned asymmetric subunits, microtubules have an intrinsic polarity. This is reflected in their growth, the fast-growing (plus) end adding or losing subunits with much greater avidity than the other, slower-growing minus end. In the interphase animal cell, microtubules are assembled with a common polarity, the minus ends being embedded in pericentriolar material, the plus ends being free to grow and shrink and explore their cytoplasmic environment. This arrangement is of enormous significance, as it provides a directional framework for cytoplasmic motor proteins such as dynein and kinesin to orchestrate a bidirectional traffic flow of vesicles and organelles. At mitosis, too, the polar assembly of spindle microtubules from the now duplicated centrosomes is essential for the establishment of balanced forces operating on sister kinetochores.

Up to now, the way that this polarity was achieved was entirely unknown. The key is almost certainly γ -tubulin, which was originally identified on the basis of its interaction with β -tubulin. As Zheng *et al.*¹ point out, if β -tubulin interacts with the α subunit in the microtubule organizing centre, then the α subunit is always distal to its organizing centre and polarity is *ipso facto* established.

The only possible cloud on the horizon of this appealing model is that most interesting things in biology come in pairs. If α -tubulin has its β counterpart, can we expect that γ has its hitherto undiscovered δ ? □

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