Constraints and opportunities inherent in a cellular existence in which the living protoplast is surrounded by a more-or-less rigid wall have given rise to a number of uniquely botanical modes of cytoskeletal form and function. These are summarized here, with special reference to the concept of a structurally and functionally integrated cytoplasmic matrix.

The cell wall possesses at least some of the shape-maintaining properties that, in animal cells, are based on the cytoskeleton. A simple demonstration of this is the inability of a plant cell protoplast to withstand the forces of surface tension that it meets when it is removed from within its cell wall: it generally rounds up to a sphere, irrespective of its original shape.

The cell wall influences cytoskeletal functions in other, less obvious ways. For instance, because shared cell walls allow only slight adjustments to the relative positions of neighboring cells, plants must regulate very precisely the site and plane in which they divide and insert new walls. The mechanism is cytoskeletal, involving the preprophase band (PPB), a specialized array of microtubules (MTs). The shape of the wall itself is largely determined by its directional yielding to hydrostatic turgor pressures, and in turn this geometry is related to the initial orientation of its cellulose microfibrils. MT arrays underlying the plasma membrane appear to participate in regulating wall microfibril orientation, providing an indirect cytoskeletal control over the shape that the cell will assume when it expands. Control of both wall insertion and wall shaping thus is at least partly mediated by MTs. Cells so large that diffusion is an insufficient means of transporting solutes along intracellular and intercellular pathways commonly develop, and in such cases intracellular motility based on actomyosin becomes prominent. Although presumably a modification of the system which, in animals, changes cell shape and drives cell migration, its function in large plant cells is primarily to distribute metabolites and organelles. Nevertheless, within the confines of the wall, the shape of the protoplast can change with dramatic speed. Finally, cell walls normally allow only small solutes to reach the plasma membrane, so that cytoskeletal functions associated with bulk endocytosis are not conspicuous in plant cells.

Despite the specifically botanical context of these activities, plant cytoskeletal components share many features with their counterparts in animal cells. The major difference appears to be a lack of intermediate filaments. There is as yet no strong evidence that this category of cytoskeletal element occurs in plants, although few studies have been directed to the question. If they indeed are absent, it could be generalized that the plant cell wall has subsumed their roles, in addition to modifying the forms and functions of the remaining components of the cytoskeleton.

Microtubules

Plant tubulin (for recent reviews, see references 15 and 31) is not exactly like animal tubulin, though it does polymerize in vitro to make MTs (33, 34). Its drug sensitivity is different (15, 35, 36) and its α-subunit resembles that of Physarum on one-dimensional gels (29, 30, 33, 56). An antibody that is specific for tyrosylated α-tubulin (50) gives immunofluorescence reactions with all categories of MT array in higher plant cells (Fig. 1).

The MTs of meristematic plant cells pass through sequential changes in position and functioning (for immunofluorescence visualizations, see references 51–53). The interphase and preprophase arrays in the cell cortex are specifically oriented, but the polarizing influences underlying these orientations are of essentially unknown nature and origin. The succession of arrays convincingly demonstrates the ability of the plant cell cytoskeleton to develop a high degree of order, reflecting the polarity of the cell as a whole and often the polarity of the tissue or organ in which the cell lies. Until recently the existence of the cell wall has prevented fluorescent antibody localizations from being carried out on intact tissues, but this limitation has now been overcome through the use of polyethylene glycol embedding (Wick, S. M., and J. Duniec, unpublished data). Fig. 1 shows how this method enables the organization of the various types of MT to be examined in...
FIGURE 1  Allium root meristem embedded in polyethylene glycol 6000, sectioned, the medium removed, and the section processed for indirect immunofluorescence using rat monoclonal antitubulin, in phase-contrast (a) and fluorescence (b) views. Anaphase spindles (1); mature phragmoplasts (2); early phragmoplast (3). PPBs also react (not shown). x 540.

populations of cells that are developing in coordination in a meristem.

In general, the MTs of the interphase cortical arrays lie normal to the predominant axis of cell expansion, congruent with newly deposited cell wall microfibrils. The PPB is not necessarily oriented in the same direction as the interphase arrays. Many developmentally important categories of cell division involve precise shifts in orientation, the position of the PPB always predicting the site and plane of placement of the cell wall that is to be formed at telophase. Whatever its orientation, the PPB is physically linked to the nucleus, allowing the two to be retained as a complex when the surrounding cytoplasm is removed (Fig. 2) (51–53). The mitotic spindle appears to be the least controlled of all stages, at least in respect to its initial orientation. Its axis is usually approximately normal to that of the PPB site, but it can deviate significantly. Any initial misalignment is corrected in anaphase-telophase by a guidance mechanism that is sensitive to antiactin drugs (38) and centered on the PPB site, although the MTs of the PPB are no longer present. The phragmoplast is initiated as an independent MT system at the equatorial plane of the mitotic figure (which by then may or may not have become aligned). Its microtubule-organizing center (MTOC) is planar and extends centrifugally toward the PPB site. The new cell wall appears as a progressively consolidating plate of membranes and contained wall material following the extending margin of the phragmoplast toward the parental walls. The eventual fusion of new and old walls approximately bisects the PPB site (for a review, see reference 14).

The phragmoplast is the only one of the successive arrays to have a distinct MTOC. The MTs that are generated there have their plus ends at the planar MTOC, and they extend in both directions normal to that plane (8). The spindle poles originate as aggregates of MT focal points at the nuclear surface (53). Manipulation of these MTOCs is possible with drugs such as isopropyl-N-(3-chlorophenyl)carbamate (CIPC), which apparently fragments the organizing capacity of mitotic MTOCs. Like its parent drug isopropyl N-phenylcarbamate (21), CIPC produces multipolar spindles (Fig. 3a). Numerous nuclear fragments may be separated during anaphase, and phragmoplasts subsequently form between all adjacent ones, resulting in branched cell plates (Fig. 3b and c). The drug aminopyrine (4-dimethylaminoantipyrine) also interferes with certain transitions in MT arrays, presumably by inhibiting the normal progression of MTOC activity; thus it causes formation of double-star configurations at late anaphase (37 and Fig. 3d and e) and prevents radial expansion of the phragmoplast (Fig. 3f).

The site of origin of cortical arrays and their MTOCs is problematical. The available evidence shows a diversity of phenomena in mosses, ferns, and flowering plants.

Moss: In vegetative cells of the moss Sphagnum the interphase cortical MTs appear to emerge from a diffuse zone between the telophase nuclei and the new cell wall, presumably taking up positions on selected cell faces by some form of self-assembly (44). Much more distinct MTOCs occur in meiocytes of mosses (1).

Ferns: Two studies of ferns have revealed foci consisting of electron-dense matrix material, vesicles or particles, and radiating MTs. They have been referred to as putative nucleating sites in Azolla root tip cells (for a review, see reference 13) and developing stomata (4) and as MTOCs in Adiantum stomata (10). They have a characteristic location close to, or at, the edges of the cell faces over which the MT array will form. They appear when both interphase and preprophase arrays are developing, and examination of cells that engage in successive rounds of division shows that they can reappear at the same edge in sequential cell cycles. This implies that there is a “memory” at such sites, just as the PPB site retains populations of adjacent ones. PPBs also react (not shown). x 540.

FIGURE 2  Linkages between the PPB and the nucleus before establishment of the mitotic spindle. Isolated PPB-nucleus complexes seen in side (a) and face (b) views. b shows MTs extending from PPB to nucleus. Allium. (a) x 1,500. (b) x 1,000.
FIGURE 3 Drug treatments in Allium root tip cells: 1 mM CIPC induces multipolar prophase spindles (poles indicated by arrows in a); branched phragmoplasts (e.g., partitioning six nuclear fragments in b); or combinations of normal and branched phragmoplasts (e.g., separating five nuclei in c). (a) × 1,300. (b) × 1,250. (c) × 1,040. 2.3% aminopyrine induces star-shaped anaphases centered on tubulin-rich areas (d and e), and abnormally narrow phragmoplasts (f). At this stage the nuclei (n) are rounding off and the phragmoplast would normally have extended to the parental walls (bars). (d and e) × 1,300. (f) × 1,500.

Reconstructions of the detailed features of cortical arrays (16, 46) indicate that MT interactions must be developmentally and/or functionally important. Certainly the distribution of foci is insufficient to account for all but the most gross aspects (e.g., foci tend to appear along edges lying normal to the predominant orientation of MTs in the developing array). MT-associated components could, however, assist in a self-ordering process, and their localization could account for observed subtleties such as one MT passing from one group to another across the intervening space.

It now seems probable that the conventional methods of preparing specimens for electron microscopy are not as good as freeze-substitution for preserving details of MT associations in plant cells. Figs. 5-8 illustrate this point, showing the general preservations of MTs and microfilaments, examples of extensive inter-MT bridging and the presence of fine fibrils lying parallel to MTs and occasionally bridged to them and to other filaments traversing the cytoplasmic matrix (Tiwari, S. C., unpublished). These features have also been seen in conventional preparations, e.g., as a herringbone pattern of inter-MT bridges (16), as other less striking instances of MT-MT and MT-membrane bridges (12, 46), and as fibrils lying parallel to MTs in a developing shoot meristem (17), guard cell protoplasts (17), root hairs (45, 46), and root tip cells (11, 19), where (as in fungal cells [23]) they have been tracked over short distances by serial sectioning (Fig. 9). The parallel fibrils seem to be markedly clearer after good freeze-substitution (Figs. 5 and 8; for Tradescantia stamen hair cells, Hepler, P. K., and Callaham, D., personal communication; for fungal cells, references 20 and 22-25). This association closely resembles that formed in vitro between MTs, actin, and microtubule-associated protein (MAP)-2 (41). As seen in Fig. 5, it appears in only a small proportion of the MTs, hence its possible role in determining the geometry of the arrays or as part of force-generating mechanisms that have been hypothesized in relation to MT-directed cellulose deposition (19) is conjectural. Decoration with heavy meromyosin (45) and fluorescence microscopy with rhodamine-labeled phalloidin (22, 24) have shown that F-actin can lie parallel and close

FLOWERING PLANTS: The situation in flowering plants is different. Evidence for foci is scant, but they have been seen at cell edges in root tips of Cyperus and Phleum (12) and in stomata of Zea (9) and sugar cane (Busby, C. H., unpublished observation). Foci seen in Phleum stomata may be less localized (39). However, immunofluorescence studies of onion and other root tip cells have not given any evidence for foci located solely in restricted regions of the cell cortex. Rather, the reinstatement of new arrays seems to involve gradual appearance of MTs between the nucleus and all parts of the cortex and the appearance of randomly arranged MTs along cell faces during cytokinesis, followed by disappearance of the former and ordering of the latter (Wick, S., unpublished observation) (Fig. 4). A transition from random to more oriented arrays is also seen in regenerating protoplasts (48).
to MTs in root hairs and fungal cells. MAP-2 has binding sites for both F-actin and tubulin (43). However, the only biochemical investigation of MAPs in higher plants concerns a calmodulin-like protein which coisolates with azuki bean tubulin (32), and as yet there is no evidence for a botanical homologue of MAP-2. Immunofluorescence studies with antibodies to spinach calmodulin indicate a strong reaction with the phragmoplast region (Fig. 10), with the mitotic apparatus, and occasionally with PPB as well (Muto, S., and Wick, S. M., unpublished observation).

**Microfilaments**

Cytoplasmic microfilaments occur in plant cells as single filaments or as bundles (Fig. 5). Both categories have been identified as F-actin by meromyosin decoration (28, 45). Fig. 11 shows a relatively unordered array of bundles traversing vacuoles and in the peripheral cytoplasm of a stamen hair cell as visualized with NBD-phallacidin. Fig. 12a and d shows the much more ordered system found in Chara as detected by immunofluorescence microscopy. As is the case with MTs, good freeze-substitution can give improved preservation of microfilaments in higher plant cells (Fig. 5) (for references on freeze-substitution of microfilaments in fungal hyphae, see references 23 and 24).
The polarity of the F-actin filaments within bundles is uniform in the most highly ordered systems (28, 56), correlating with associated unidirectional cytoplasmic streaming toward the “barbed” ends. Nonuniform polarity in small bundles, correlating with bidirectional particle movement, also occurs (45). Mechanisms of force generation at microfilaments of F-actin in plant cells are discussed in references 27, 47, 54, and 55 and will not be considered here.

Little is known about the development of microfilament arrays in plant cells or about factors that regulate the association into bundles. Bundles in the peripheral cytoplasm of Vallisneria leaf cells evidently share the same polarity, as judged by the direction in which the chloroplasts move; if the bundles are broken down by cytochalasin treatment and allowed to regenerate, their polarity is once again uniform, though there is a 50% chance that it will not be in the same direction as before (26). Evidently, the cells regenerate and deploy a completely new array of bundles. By contrast, if existing bundles are destroyed locally, the exposed “pointed” and “barbed” ends are available as seeds on which regrowth can occur. A study of Chara (Williamson, R. E., U. Hurley, and J. Perkin, unpublished) shows that this type of regrowth is strictly polarized. The “barbed” end is preferred and regrows after a lag phase, while the “pointed” end remains essentially static for many hours. This plant system therefore has the same polarity of assembly as comparable bundles from animal sources (e.g., 40), and the relative inactivity of the nonpreferred end in vivo resembles that of the same end in vitro preparations of animal F-actin held under physiological conditions (5). The regenerating bundles in Chara seem to become oriented passively by the continuing flow of endoplasm past the zone where regeneration is occurring. De novo formation of new bundles, which are less ordered in their growth orientation, also occurs as a minor component of the Chara system.

The bundles of F-actin in Chara cells lie at the interface between the mobile endoplasm and the stable ectoplasm. It has long been evident that the bundles participate in the spatial organization of the stable region in that they lie along files of chloroplasts (Fig. 12a and b). A recent finding that may also be relevant to higher plant cells is that fibrillar components that are immunologically related to components of the actin bundles have been detected elsewhere in the stable cortical cytoplasm by raising a library of monoclonal antibodies to components of the Chara cortex (Williamson, R. E., J. Perkin, and U. Hurley, unpublished). For example, antibody CC2 binds to the actin bundles and, in some cells, to fibrils lying between the chloroplasts and the plasma membrane that are uninterrupted by the neutral line and oriented predominantly transverse to the main array of bundles (Fig. 12c and d). Whether the antibodies detect proteins that are identical to those in the actin bundles or ones that merely share an epitope remains to be seen. It will be important to see whether these fibrils occur in higher plant cells, where they could be associated with the cortical MT arrays and could aid in stabilizing the surface zone where the MTs must maintain their orientation even when cytoplasmic streaming is occurring in the vicinity.

Microtrabeculae

Early work on plant cells has indicated that an ordered cytomatrix exists in some situations (reviewed by Porter, K. R. [42], in this supplement). Direct support for the concept has come recently from detection of three-dimensional networks similar to the microtrabecular lattice in sections from which the embedding medium has been removed. This morphology has been seen in a variety of cell types by removing resin from epoxy sections and shadow-casting (49). Some freeze-substituted preparations also indicate fibrillar interconnections between MTs and the ground substance (Fig. 6). The polyethylene glycol technique also has revealed extensive interconnections between membrane systems of root tip cells. The familiar fixation image was restored when the sections
were reembedded in epoxy resin (18). A. Scholler and J. Pickett-Heaps (personal communication) have also used polystyrene glycol embedding and high-voltage electron microscopy to visualize a microtrabecular lattice throughout the cytoplasm of cells in an alga, Protosiphon, and in onion root cytoplasm of cells in an alga, Protosiphon, and in onion root cytoplasm of cells in an alga, Protosiphon, and in onion root cytoplasm of cells in an alga, Protosiphon, and in onion root cytoplasm of cells in an alga, Protosiphon, and in onion root cytoplasm of cells in an alga, Protosiphon, and in onion root cytoplasm of cells in an alga, Protosiphon, and in onion root cytoplasm of cells in an alga, Protosiphon, and in onion root.

General Consideration of Large-Scale Order in Plant Cell Cytoskeleton

There are several locations in plant cells where a three-dimensionally stabilized matrix is likely to be especially important. Some have already received mention, for example the cell cortex, where MTs and associated components are not swept away by cytoplasmic streaming and are believed to enter into a functional interaction by which cellulose-synthetases lying in or on the plasma membrane receive spatial guidance.

Structural integration of PPBs and nuclei and of PPB sites and phragmoplasts has also been mentioned, and it is now relevant to widen the context. The site at which a higher plant cell will divide is determined before mitosis, and in some cases before PPB formation, as evidenced by the appearance of a specifically placed raft of cytoplasm known as a phragmosome (14). Phragmosomes are best seen in vacuolated cells, but may also occur as differentiated but not readily distinguishable cytoplasm in less vacuolated cells. They retain their position in the cell over considerable periods. The nucleus undergoes mitosis in them, the phragmoplast and cell plate later extending within the phragmosomal cytoplasm toward the parental walls. In a number of reproductive cell types in which PPBs do not develop, the site of the future cell plate becomes marked by planar aggregations of mitochondria, lipid droplets, and, sometimes, plastids (14). Additional mechanisms exist in cells that have only one plastid, ensuring that plastid division is geared, both temporally and spatially, to nuclear division. The chloroplast moves (but only when the plane of cytokinesis is such as to require movement) so that the isthmus of its division is in the plane delimited by the PPB. Each daughter cell thus receives a daughter plastid (2).

Clearly, the PPB is only one component of the cytoskeletal preparations for spatial control of cell division, which ramify from the cell surface to the nucleus and also involve other organelles. The structural basis of this three-dimensional organization and integrated cellular choreography is not understood.

Finally, nondividing plant cells are not to be viewed as collections of randomly arranged endoplasmic organelles within a more organized ectocytol. There are many examples, too numerous to review here, of specific placement of cell components in relation to (a) vectorial cell functions such as eccrine or granulocrine secretion, (b) polarized growth or other developmental events, and (c) metabolic exchanges among organelles. Together with the examples of specific depolymerization of cytoskeletal structures already given, these widespread phenomena demonstrate the capacity of the cytoplasmic matrix of plant cells to participate in structural ordering and functional interactions that may, indeed, be absent only in rapidly streaming endoplasm.

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