Giant Axonal Neuropathy: A Conditional Mutation Affecting Cytoskeletal Organization

MICHAEL W. KLYMKOWSKY and DOROTHY J. PLUMMER
Departments of Molecular, Cellular, and Developmental Biology, University of Colorado, Boulder, Colorado 80309

ABSTRACT Giant axonal neuropathy (GAN) results from autosomal recessive mutations (*gan*$^-$) that affect cytoskeletal organization; specifically, intermediate filaments (IFs) are found collapsed into massive bundles in a variety of different cell types. We studied the *gan*$^-$ fibroblast lines WG321 and WG139 derived from different GAN patients. Although previous studies implied that the *gan*$^-$ IF phenotype was constitutive, we find that it is conditional. That is, when cells were grown under the permissive condition of medium containing over 2% fetal calf serum, most cells had normal IF organization. IF bundles formed when *gan*$^-$ cells were transferred to the nonpermissive condition of low (0.1%) serum. Microtubule organization appeared normal in the presence or absence of serum. The effect of serum starvation was largely blocked or reversed by the addition of BSA to the culture media. We found no evidence that the *gan*$^-$ phenotype depends upon progress through the cell cycle. We discuss the possible role of serum effects in the etiology of GAN and speculate as to the molecular nature of the *gan*$^-$ defect.

Giant axonal neuropathy (GAN)[1] is a rare, slowly progressive central–peripheral distal axonopathy (1, 40, 41); symptoms first appear in children between the ages of 3 and 5 yr. The identification of related siblings with GAN (21), parental consanguinity of some GAN patients (11, 18, 41), studies of a genetic disease with similar symptoms in inbred dogs (7, 8), and the persistence of aberrant intermediate filament (IF) phenotype in cultured cells derived from GAN patients (37–39; see below) indicate that GAN is a genetic disease, and results from an autosomal recessive mutation(s) (*gan*$^-$). For the student of cell biology, GAN is of particular interest because it is one of only a handful of mutations known to affect cytoskeletal organization and function. Most of these mutations affect either actin or tubulin genes; they include mutations in *Saccharomyces cerevisiae* (35, 47), *Schizosaccharomyces pombe* (50), *Aspergillus* (34, 46), *Drosophilia melanogaster* (23, 24), *Caenorhabditis elegans* (15), and cultured Chinese hamster ovary cells (4–6, 22). *gan*$^-$ is the only mutation known to affect IF organization specifically.

Diagnosis is of GAN is based upon the presence of large, focal accumulations of neuronal IFs that cause regions of nerve axons to "balloon." These IF bundles first appear distally in neurons that project into the periphery; as the disease progresses, central neurons that do not project into the periphery can also become affected (25, 40). Ultrastructural examination of *gan*$^-$ tissues reveals abnormal IF bundles not only in neurons, which express the neuron-specific triplet of IF subunit proteins; but also in astrocytes, Schwann cells, endothelial cells, and skin fibroblasts (40, 41), which express their own distinctive IF subunit proteins (see reference 36 for review). In addition, all but two of the GAN patients reported (20, 40) have had unusually kinky hair (1, 41), which is of interest because hair is composed of epithelial IF (10, 51).

To characterize the molecular defect underlying GAN, we have studied two independently isolated, *gan*$^-$ human fibroblast cell lines. In contrast to previous reports (37–39), we find that *gan*$^-$ mutations have a conditional, not a constitutive IF phenotype, and that this phenotype appears to be mediated by serum factors.

MATERIALS AND METHODS

Cell Culture: We studied the *gan*$^-$ skin fibroblast lines, WG321 and WG139, and the normal (*GAN*$^+$) human foreskin fibroblast line, MCH7, which

[1] *Abbreviations used in this paper:* anti-IF(1.4E9), monoclonal anti-intermediate filament antibody; anti-MIg-Fl, fluorescein-conjugated, affinity-purified goat anti-mouse immunoglobulin antisera; anti-MIg-Rd, tetramethylrhodamine-conjugated, affinity-purified goat anti-mouse immunoglobulin antisera; anti-MTOC, monoclonal antimicrotubule-organizing center; GAN, giant axonal neuropathy; *gan*$^-$, autosomal recessive mutations; IF, intermediate filament; MEM, minimal essential medium; MTOC, microtubule-organizing center.

THE JOURNAL OF CELL BIOLOGY · VOLUME 100 JANUARY 1985 245–250

were obtained from the Repository of Mutant Human Cell Stains, deBelle Laboratory for Biochemical Genetics/McGill University-Montreal Children's Hospital Research Institute. Cells were grown in minimal essential media, Eagle's modification (MEM), supplemented with 10% heat-inactivated fetal calf serum, 10 mM HEPES, and antibiotics, either penicillin/streptomycin or gentamycin (10% MEM). Alternatively, 10% Nu-Serum (Collaborative Research Inc., Waltham, MA), 6–20 mg/ml BSA, Cohn fraction V (Sigma Chemical Co., St. Louis, Mo.—lot 113F-0273, described as 96–99% albumin), or 10 mg/ml ovalbumin (Sigma Chemical Co., grade V—lot 33F-8110, described as electrophoretically pure and ~99% pure) were substituted for fetal calf serum. The purity of the BSA used in our experiments was over 98% as determined by PAGE (30).

Cells were grown at 37°C in a humidified, 5% CO_2 incubator, and were used at low passage number (<12) and low total cell doublings (estimated to be <40). Cells were passaged using trypsin and EDTA. For immunofluorescence microscopy, cells were grown on glass coverslips. Cultures were fed every 3–4 d with fresh 10% MEM; experiments were performed 8–14 d after plating. When media conditions were changed, cultures were washed three times with warmed MEM containing HEPES, and then fed with medium containing appropriate additives. Cells could be maintained in 0–0.1% serum for over 5 d without apparent effects on viability. Occasionally we observed wholesale cell death in some colonies in response to repeated cycles of serum starvation; although some colonies died, the majority appeared normal. In addition, we observed what appeared to be an increase in the variation of the response of *gan*⁻ cells to serum conditions with increasing age in culture; the results reported here are based solely nonsenescent cells, passaged less than 12 times, and subjected to only a single cycle of serum starvation.

Monoclonal Antibodies and Immunofluorescence Microscopy: IFs were visualized using the monoclonal anti-intermediate filament antibody anti-IF(1.4E9). Anti-IF(1.4E9), an IgM, was generated using cytoskeletal extracts as immunogen and reacts with human, chick, and mouse vimentin and *Potoroo tridactylus*-derived PtK_1 kidney epithelial keratins as determined by Western immunoblot analysis and immunofluorescence microscopy (Klymkowsky, M. W., work in progress). Microtubule organization was visualized by using the monoclonal antitubulin antibody 4A1 (antitubulin) generated by Dr. M. Fuller (University of Colorado) and a monoclonal anti-microtubule-organizing center antibody C29 (anti-MTOC) generated by T. Mitchison (University of California, San Francisco).

Immunofluorescence microscopy was carried out as described previously (27, 28). For double immunolabeling with anti-MTOC and anti-IF(1.4E9), anti-MTOC was applied first, labeled with fluorescein-conjugated, affinity-purified goat anti-mouse immunoglobulin antisera (anti-MIg-Fl)(1:100), followed by anti-IF(1.4E9) and tetramethylrhodamine-conjugated, affinity-purified goat anti-mouse immunoglobulin antisera (anti-MIg-Rd)(1:100). Under these conditions, the anti-IF(1.4E9) and anti-MIg-Rd antibodies labeled the anti-MTOC/anti-MIg-Fl complex; the small size of the microtubule-organizing center (MTOC) led to image confusion in only a small and readily identifiable region of the cell.

Antibody incubations were carried out for 20 min at room temperature. Conjugates were purchased from Cappel Laboratories (Cochranville, PA); there was no noticeable, nonspecific labeling by any of the conjugates.

Coomassie Labeling of Cells: To examine the overall organization of IFs in cell colonies, we employed a slightly modified version of the Coomassie Brilliant Blue-staining procedure developed by Pena (37). Cultures were extracted with 60 mM PIPES, 25 mM HEPES, 10 mM EGTA, 2 mM $MgCl_2$, 0.02% NaN_3, 0.15% Triton X-100 (42), and then fixed for 10 min at room temperature with 4% formaldehyde in PBS. After fixation, cultures were stained with 0.2% Coomassie Brilliant Blue R250 in 7% acetic acid and 46.5% methanol for 5 min, destained with 5% methanol/5% acetic acid, and then air-dried. Coomassie-stained cultures were viewed under bright-field optics; cells with IF bundles could be identified unambiguously (Fig. 1, *C* and *F*). Typically, between 40 and 50% of the cells (200–1,200 cells) within each of 10–14 independent colonies were examined for each experimental condition. In certain cases (see Fig. 3*B*), all of the cells in the colonies examined were scored. Colonies were chosen for examination at random and once chosen no colony was discarded.

Autoradiography: Cells undergoing active DNA synthesis were labeled by incubating cultures for 24 h in 1 μCi [^{3}H]thymidine (New England Nuclear, Boston, MA) per milliliter of media. After Coomassie staining and air-drying (see above), culture dishes were coated with Kodak NTB-2 emulsion diluted 1:1 with water. The emulsion was dried at room temperature, exposed at 0°C for 7–10 d, and developed with D19, as described by Stein and Yanishevsky (48). Nuclei with >50 autoradiographic grains over them were scored as labeled: this value was chosen to provide an unambiguous index of labeling; lower numbers of autoradiographic grains were often obscured by the Coomassie Brilliant Blue staining of nuclei (see Fig. 1). Most nuclei (>80%) were very heavily labeled, i.e., >500 grains. In this series of experiments, background labeling was <1 grain per 100 μm^2.

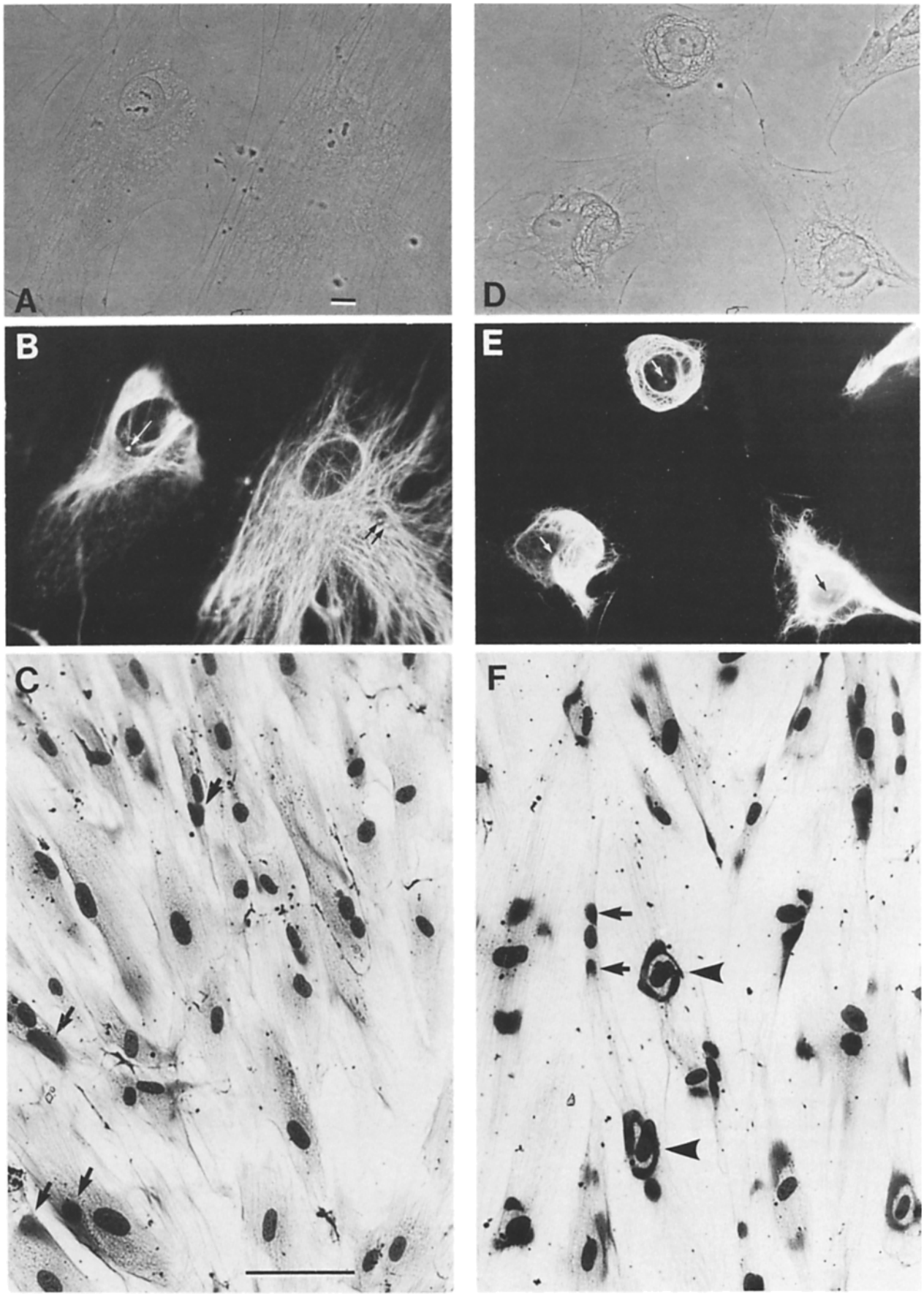
RESULTS

Pena first described the presence of large bundles of vimentin-type IFs in the cultured *gan*⁻ fibroblast lines WG321, WG129, and WG791 (37, 38). These reports claimed that >90% of the cells contained IF bundles; no mention of variations in the percentage of cells containing IF bundles was made. We were therefore surprised to find in our initial immunofluorescence studies that both WG139 and WG321 cells showed either a normal or a "collapsed" IF phenotype (Fig. 1, *A–C*), and that the percentage of cells containing detectable IF bundles was often <20% (Fig. 1 *C*). As reported by Pena et al. (39), microtubule organization appeared normal in all cells (Fig. 2).

We initially assumed that the variability in IF organization in *gan*⁻ cells was due to difference between clones. We have observed apparent clonal variations in the organization of HeLa (31) and LCC-PK_1 cell IFs (Klymkowsky, M. W., unpublished observations). To test the possibility that clonal variation was the cause of the discrepancy between our results and those of Pena, 200–400 WG321 or WG139 cells were plated into 60-mm diam tissue culture petri dishes; examination of these cultures within 24 h of plating confirmed that >80% of the cells were single, isolated cells. Within 8–12 d colonies had grown up from these cells, and the presence of IF bundles was assayed using the Coomassie Blue-staining method; every colony contained some cells with and some without IF bundles (Figs. 1 *C* and 3*A*). The percentage of cells with IF bundles varied among colonies within the same culture (Fig. 3*A*).

Reasoning that variations in IF organization between clonally derived *gan*⁻ cells could be due to their relative positions within the cell cycle, cells growing in colonies were synchronized by serum starvation (0–0.1% fetal calf serum). Within 24 h, the majority of serum-starved WG139 and WG321 cells contained IF bundles (Figs. 1 *F* and 3*A*). Examination of serum starvation-induced IF reorganization by immunofluorescence microscopy revealed that the initial phases of IF

FIGURE 1 IF organization in WG321 cells grown continuously in 10% MEM (*A–C*) or 24 h after transfer to 0.1% fetal calf serum containing-medium (*D–F*) was examined by indirect immunofluorescence microscopy (*A* and *D*, phase optics; *B* and *E*, rhodamine optics) or Coomassie Brilliant Blue staining (*C* and *F*). For immunofluorescence microscopy, cells were labeled with anti-MTOC, anti-MIg-Fl, anti-IF(1.4E9), and anti-MIg-Rd. IF organization appeared normal in most cells grown in 10% MEM, although IF bundles were found in some (*A* and *B*). When maintained in 0.1% serum, most cells contained IF bundles (*D* and *E*). Arrows in *B* and *E* mark the positions of MTOC as determined by examination of cells under fluorescein optics (not shown). The percentage of cells with normal and collapsed IF can better be judged by Coomassie staining: few cells contained IF bundles in 10% MEM (arrows, *C*), whereas in 0.1% serum (*F*) the great majority of cells contained IF bundles. One or two IF bundles were found in most cells, and these assumed a number of different shapes, ranging from compact bundles (arrows) to perinuclear rings (arrowheads). Bars, 10 μm (*A*); 100 μm (*C*). × 410 (*A*, *B*, *D*, and *E*); × 190 (*C* and *F*).


A
D
B
E
C
F

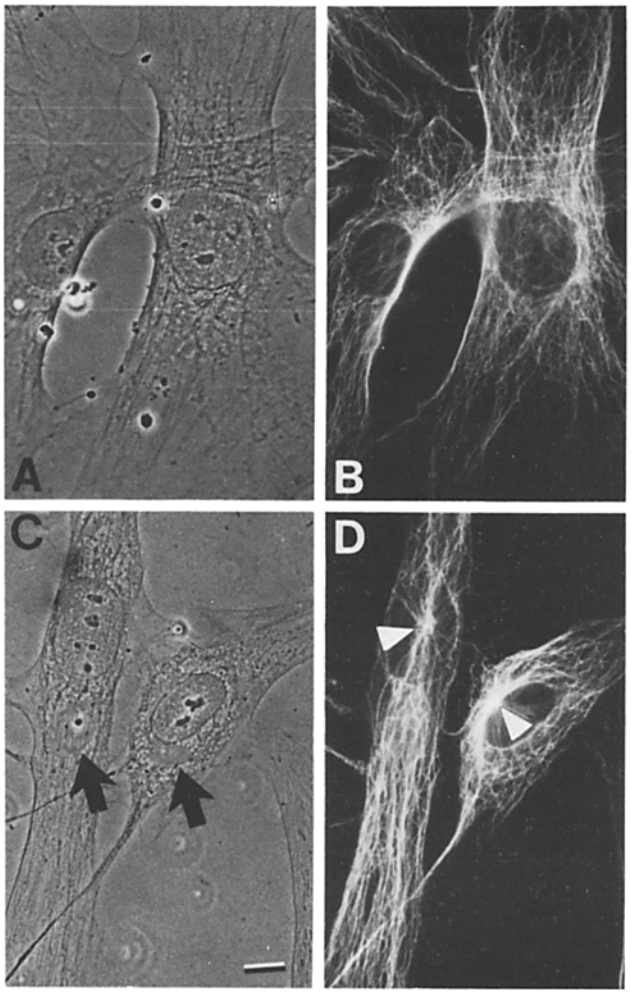


FIGURE 2 The organization of microtubules in WG321 cells grown in the presence (*A*, phase optics; *B*, fluorescein optics) or absence (*C*, phase optics; *D*, fluorescein optics) of fetal calf serum was revealed by immunofluorescence microscopy using antitubulin and anti-Mlg-Fl. Microtubule organization appeared normal in the presence or absence of serum. IF bundles are visible under phase optics (arrows in *C*) in cells grown in the absence of serum; the apparent positions of MTOC can be discerned from the pattern of microtubule labeling (arrowheads in *D*). Bar, 10 μm. × 450.

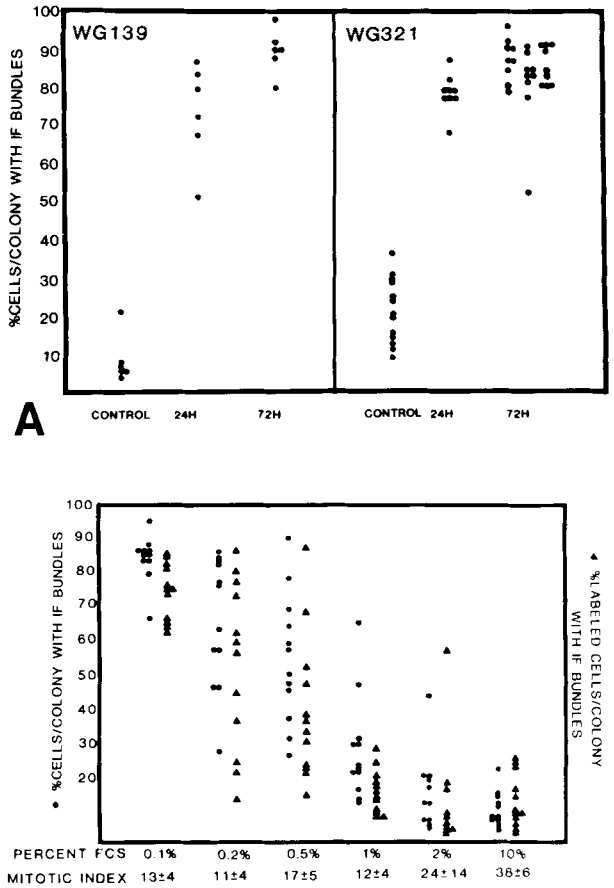


FIGURE 3 (*A*) The percentage of IF bundles found in colonies of WG139 cells (*left*) and WG321 cells (*right*) was low in cultures grown in 10% fetal calf serum-containing media (*CONTROL*). Within 24 h (*24H*) after transfer of sister cultures 0.1% fetal calf serum-containing media, the percentage of cells with IF bundles had increased considerably; after 72 h (*72H*) most but not all cells contained IF bundles. Three separate experiments are plotted for the 72-h serum-starvation response of WG321 cells. (*B*) To titer the effect of fetal calf serum on IF phenotype, WG321 cells were grown as colonies for 8 d in 10% MEM and then transferred into media containing varying amounts of fetal calf serum. After 24 h, 1 μCi/ml [^{3}H]thymidine was added to each culture. The cells were examined after 24 h in [^{3}H]thymidine by Coomassie Brilliant Blue staining and autoradiography. 10–12 colonies on each plate were chosen at random; all cells were counted for the presence of IF bundles and nuclear autoradiographic labeling. The percentage of fetal calf serum (*PERCENT FCS*) and the percentage of cells labeled with [^{3}H]thymidine (*MITOTIC INDEX*) are noted on the bottom of the graph. The percentage of all cells containing IF bundles is shown with circles; triangles indicate the percentage of autoradiographically labeled cells with IF bundles.

collapse were evident within 4 h after the removal of serum (not shown), and essentially complete in most cells within 24 h (Figs. 1, *D–F* and 3*A*). Parallel studies of colchicine-induced IF bundle formation in normal *GAN*$^+$ MCH7 cells indicated that the time course of IF collapse in *gan*$^-$ cells is similar to that observed in response to microtubule depolymerization (not shown). In contrast to drug-induced IF collapse, microtubules remained intact within serum-starved, *gan*$^-$ cells (Fig. 2, *C* and *D*). Because both WG321 and WG139 cells showed similar conditional IF phenotypes (Fig. 3*A*), we chose to carry out most of our experiments using the WG321 cell line.

We have never observed a serum starvation-induced collapse of IF in normal MCH7 (*GAN*$^+$) fibroblasts; their IF networks appeared normal by both immunofluorescence microscopy and Coomassie staining in the presence or absence of serum (not shown). Only rarely, i.e., in <0.1% of the cells, were small IF bundles found in MCH7 cells (not shown).

The collapse of IF was readily reversed by returning serum-starved cells to fetal calf serum-containing media (Fig. 3*B*). Normal IF organization as also found when Nu-Serum, a low-protein serum substitute, was used instead of fetal calf serum (Fig. 4, *a* and *g*). Recovery of a normal IF phenotype was complete in most cells after 24 h in fetal calf serum or Nu-Serum (Figs. 3*B* and 4*g*). Titration of the fetal calf serum effect on IF organization revealed a threshold level of ~1% serum (Fig. 3*B*). There was a clear increase in the variability of IF phenotype between colonies at serum concentrations between 0.2% and 0.5% (Fig. 3*B*), suggesting that the *gan*$^-$ IF phenotype of different WG321 cell clones had different serum-threshold levels.

Immunofluorescence labeling of WG321 cells with antitubulin antibody revealed normal, intact microtubule systems

in both the presence (Fig. 2, *A* and *B*) and absence (Fig. 2, *C* and *D*) of serum. IF bundles can often be identified under phase-contrast optics (Fig. 2*C*—arrows), there seemed to be little interaction between the microtubule system and IF bundles in most cases (Fig. 2, *C* and *D*). The MTOC remained near the nucleus (Figs. 1 and 2*D*) in most cells (although see Fig. 1*B*), and sometimes appeared to associate with the periphery of the IF bundle (Fig. 1, *B* and *E*). Whether associations between IF bundles and MTOC were fortuitous or reflect significant interaction between the two remains to be determined.

Serum-induced recovery of normal IF organization occurred when DNA synthesis was inhibited by either 10 mM thymidine or 2 mM hydroxyurea (Fig. 4, *h* and *i*), which indicates that progress through the S phase of the cell cycle was not required for normal IF phenotype in *gan*$^-$ cells. Autoradiographic analysis of *gan*$^-$ cells recovering from serum starvation-induced IF collapse revealed no obvious correlation between DNA synthesis (mitotic index) and recovery of normal IF organization (Fig. 3*B*). We have not attempted to determine whether protein synthesis was required for the reorganization of IF because protein synthesis inhibitors themselves have been reported to affect IF organization (45).

The absence of a correlation between the formation of IF bundles and progress through the cell cycle led us to suspect the involvement of serum factors in producing the *gan*$^-$ IF phenotype. BSA at concentrations of 6 or 20 mg/ml prevented the formation of IF bundles in serum-deprived cells, and reversed the serum starvation-induced IF collapse (Fig. 4, *b*, *c*, *e*, and *f*). Ovalbumin added at 10 mg/ml to MEM did not prevent IF collapse (not shown), indicating that the effect of BSA was not due simply to the presence of protein in the media. The BSA used in these experiments was judged >98% pure (see Materials and Methods). Because at least 1% whole serum was required to produce the same IF phenotype, we consider it unlikely that the BSA effect was due to minor serum contaminants present in the BSA preparation. However, the effect of BSA on *gan*$^-$ IF phenotype was less complete than that of either fetal calf serum or Nu-Serum; i.e., a greater percentage of cells contained IF bundles in the presence of BSA than in the presence of either fetal calf serum or Nu-Serum (Fig. 4). There may therefore be other factors present in serum that also contribute to the control IF phenotype in *gan*$^-$ cells.

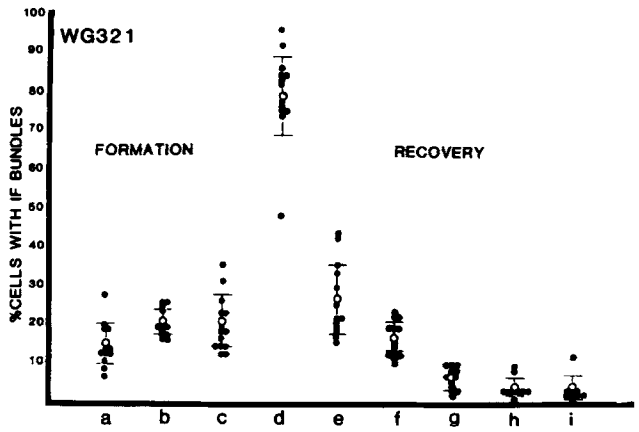


FIGURE 4 WG321 cells were grown as colonies in 10% MEM for 10 d and then transferred to either 10% Nu-Serum (a), 20 mg/ml BSA (*b*), or 6 mg/ml BSA (c) containing serum-free MEM and assayed for the presence of IF bundles 24 h later by Coomassie staining. In a second experiment, cells in sister cultures were transferred first to 0.1% fetal calf serum-containing media for 48 h (*d*) and then returned to media containing 6 mg/ml BSA (*e*), 20 mg/ml BSA (*f*), 10% Nu-Serum (*g*), 10% MEM containing 10 mM thymidine (*h*), or 10% MEM containing 2 mM hydroxyurea (*i*). After 24 h these cultures were examined by Coomassie staining. The percentage of cells containing IF bundles is plotted with the mean and standard deviation.

DISCUSSION

The *gan*$^-$ mutations affect neuronal, glial, fibroblastic, and in some cases epithelial IF (40, 41). These IF are each composed of unique proteins coded for by separate genes (36, 51). Biochemical comparison of vimentin from normal, *GAN*$^+$ and *gan*$^-$ fibroblasts reveals no obvious difference in either electrophoretic mobility or level of posttranslational modification (38; Plummer, D. J., and M. W. Klymkowsky, work in progress) suggesting that the *gan*$^-$ defect does not affect IF proteins themselves, but rather a widely distributed component involved in the control of IF organization. There is mounting evidence that normal IF organization depends upon interactions with microtubules. Linking structures between IF and microtubules have been observed by electron microscopy in neuronal (14) and non-neuronal cells (42), and disruption of interphase microtubules by any of a number of means (2, 3, 13, 16, 19, 44, 52) leads to the collapse of IF into bundles. However, in *gan*$^-$ cells IF collapse occurs even though microtubule organization appears unaltered (Fig. 2). In this the phenotype of *gan*$^-$ is similar to that produced by heat shock (49) and intracellularly injected anti-IF antibodies (12, 26–28, 33).

A number of compounds are known to induce neuronal IF disorganization when administered in vivo (reviewed in reference 29). Most of these agents cause the appearance of IF bundles in the proximal axon or within the perikaryon (29). In GAN, IF bundles form in the distal portion of axons that project into the periphery. The distal localization of IF bundles in GAN may be a result of the involvement of serum factors in the *gan*$^-$ phenotype. The cell bodies of central neurons are shielded from direct interaction with serum factors by the "blood–brain barrier." However, serum components are taken up by such neurons, and serum albumin has been shown to be the major retrogradely transported protein in sciatic nerve (9, 32). How serum factors influence IF phenotype of *gan*$^-$ cells is unclear. Morphological changes in response to serum starvation have been noted in neuroblastoma cell lines; however, in these cases α_1-, α_4-, and β-globulin, not serum albumin, were effective substitutes for whole serum (43). In addition, it remains to be explained why the first symptoms of GAN do not appear until relatively late in childhood. Perhaps IF bundles are formed earlier, but fail to produce symptoms until other events, such as myelination, occur.

Although a number of models for how *gan*$^-$ produces IF collapse are imaginable, we believe that the most likely is that *gan*$^-$ alters the interaction between IF and microtubules. That is, when cells are maintained under permissive conditions, there are enough links between microtubules and IF to maintain normal IF organization in most cells. Under nonpermissive conditions, these links are broken and IF collapse. Assuming that *gan*$^-$ causes IF collapse by disrupting the links between IF and microtubules, then a number of possible mech-

anisms by which it could act are conceivable. Because of the role of serum and, by implication, cellular metabolism in the *gan*$^-$ phenotype, we favor a model in which the effective concentration or binding affinity of linker protein(s) drops under nonpermissive conditions due to changes in either the relative rates of their synthesis, turnover, or posttranslational modification.

One hint as to molecular basis of the restrictive (i.e., serum minus) *gan*$^-$ phenotype may come from the recent report that a number of different cell types synthesize a specific ensemble of proteins during G_0 arrest, and that a subset of these "G_0 proteins" are also "heat shock" proteins (17). We are currently in the process of comparing heat shock and G_0 protein in *GAN*$^+$ and *gan*$^-$ cells.

The experimental disruption of IF organization by intracellular injection of anti-IF antibodies has no recognizable affect on either cell morphology or behavior (12, 26, 28, 31, 33). Therefore, we suspect that the symptoms of GAN and other neuropathies displaying altered IF organization are not due to the loss of normal IF organization per se, but result either from side effects due to the presence of massive IF bundles within the confines of the axon or to metabolic alterations that only secondarily affect IF organization.

We thank Dr. G. Stein for providing the tissue culture facilities used in the initial phase of this work, Dr. M. Fuller and T. Mitchison for the gift of antibodies, Dr. S. Dutcher and Dr. A. Zetterberg for helpful discussion, Dr. R. Lasek for editorial advice, and Mr. L. Browne for secretarial assistance.

This work was supported by National Science Foundation grant PCM8319169, the Council on Research and Creative Work, University of Colorado, and the Alzheimer's and Related Disease Foundation, Inc.

Received for publication 16 July 1984, and in revised form 1 October 1984.

REFERENCES

1. Ashbury, A. K., M. K. Gale, S. C. Cox, J. R. Baringer, and B. O. Berg. 1972. Giant axonal neuropathy: a unique case with segmented neurofilamentous masses. *Acta Neuropathol.* 20:237–247.
2. Aubin, J. E., M. Osborn, W. W. Franke, and K. Weber. 1980. Intermediate filaments of the vimentin-type and cytokeratin-type are distributed differently during mitosis. *Exp. Cell Res.* 129:149–165.
3. Blose, S. H., D. I. Metlzer, and J. R. Feramisco. 1984. 10-nm filaments are induced to collapse in living cells microinjected with monoclonal and polyclonal antibodies against tubulin. *J. Cell Biol.* 98:847–858.
4. Cabral, F. 1983. Isolation of Chinese hamster ovary cell mutants requiring the contiuous presence of taxol for cell division. *J. Cell Biol.* 97:22–29.
5. Cabral, F., I. Abraham, and M. M. Gottesman. 1981. Isolation of a taxol-resistant Chinese hamster ovary cell mutant that has an alteration in α-tubulin. *Proc. Natl. Acad. Sci. USA.* 78:4388–4391.
6. Cabral, F., M. E. Sobel, and M. M. Gottesman. 1980. CHO mutants resistant to colchicine, colcemid, or griseofulvin have an altered β-tubulin. *Cell.* 20:29–36.
7. Duncan, I D., and I. R. Griffiths. 1977. Canine giant axonal neuropathy. *Vet. Rec.* 101:438–441.
8. Duncan, I. D., and I. R. Griffiths. 1979. Peripheral nervous system in a case of canine giant axonal neuropathy. *Neuropathol. Appl. Neurobiol.* 5:25–38.
9. Fink, D. J., and H. Gainer. 1980. Retrograd axonal transport of endogenous proteins in sciatic nerve demonstrated by covalent labelling in vivo. *Science (Wash. DC).* 208:302–305.
10. Fuchs, E. V., S. M. Coppock, H. Green, and D. W. Cleveland. 1981. Two distinct classes of keratin genes and their evolutionary significance. *Cell.* 27:75–84.
11. Gambarelli, D., J. Hassoun, J. F. Pellissier, M. O. Livet, N. Pinsard, and M. Toga. 1977. Giant axonal neuropathy-involvement of peripheral nerve, mesenteric plexus and extra-neuronal area. *Acta Neuropathol.* 39:261–269.
12. Gawlitta, W., M. Osborn, and K. Weber. 1981. Coiling of intermediate filament induced by microinjection of a vimentin-specific antibody does not interfere with locomotion and mitosis. *Eur. J. Cell Biol.* 26:83–90.
13. Goldman, R. D. 1971. The role of three cytoplasmic fibers in BHK-21 cell motility: I. Microtubules and the effects of colchicine. *J. Cell Biol.* 51:752–762.
14. Hirokawa, N., M. A. Glicksman, and M. B. Willard. 1984. Organization of mammalian neurofilament polypeptides within the neuronal cytoskeleton. *J. Cell Biol.* 98:1523–1536.
15. Hirsh, D., J. G. Files, and S. H. Carr. 1982. Isolation and genetic mapping of the actin genes of *Caenorhabditis elegans*. *In* Muscle Development: Molecular and Cellular Control. Cold Spring Harbor Laboratory Press, Cold Spring Harbor, NY. 77–86.
16. Hynes, R. O., and A. T. Destree. 1978. 10nm filaments in normal and transformed cells. *Cell.* 13:151–163.
17. Iida, H., and I. Yahara. 1984. Durable synthesis of high molecular weight heat shock proteins in G_0 cells of the yeast and other eucaryotes. *J. Cell Biol.* 99:199–207.
18. Igisu, H., M. Ohta, T. Tabira, S. Hosokawa, I. Goto, and Y. Kuroiwa. 1975. Giant axonal neuropathy—a clinical entity affecting the central as well as the peripheral nervous system. *Neurology.* 25:717–721.
19. Ishikawa, H., R. Bischoff, and H. Holtzer. 1968. Mitosis and intermediate-sized filaments in developing skeletal muscle. *J. Cell Biol.* 38:538–555.
20. Jedrzejowska, H., and H. Drac. 1977. Infantile chronic peripheral neuropathy with giant axons. Report of a case. *Acta Neuropathol.* 37:213–217.
21. Jones, M. Z., M. A. Nigro, and P. S. Barre. 1979. Familial "giant axonal neuropathy." *J. Neuropathol. Exp. Neurol.* 38:324a. (Abstr.)
22. Keates, R. A. B., F. Sarangi, and V. Ling. 1981. Structural and functional alterations in microtubule protein from Chinese hamster ovary cell mutants. *Proc. Natl. Acad. Sci. USA.* 78:5638–5642.
23. Kemphues, K. J., E. C. Raff, R. A. Raff, and T. C. Kaufman. 1980. Mutation in a testis-specific β-tubulin in *Drosophila*: analysis of its effects on meiosis and map location of the gene. *Cell.* 21:445–451.
24. Kemphues, K. J., R. A. Raff, T. C. Kaufman, and E. C. Raff. 1979. Mutation in a structural gene for β-tubulin specific to testis in *Drosophilia melanogaster*. *Proc. Acad. Natl. Aci. USA.* 76:3991–3995.
25. Kirkham, T. H., D. Guitton, and S. G. Coupland. 1980. Giant axonal neuropathy: visual and oculomotor deficits. *J. Can. Sci. Neurol.* 7:177–184.
26. Klymkowsky, M. W. 1981. Intermediate filaments collapse in 3T3 cells after the intracellular injection of a monoclonal anti-intermediate filament antibody. *Nature (Lond.).* 291:240–251.
27. Klymkowsky, M. W. 1982. Vimentin and keratin intermediate filament systems of cultured PtK_2 epithelial cells are interrelated. *EMBO (Eur. Mol. Biol. Organ.) J.* 1:161–165.
28. Klymkowsky, M. W., R. H. Miller, and E. B. Lane. 1983. Morphology, behavior and interaction of cultured epithelial cells after the antibody-induced disruption of keratin filament organization. *J. Cell Biol.* 96:494–509.
29. Kosik, K. S., and D. J. Selkoe. 1983. Experimental models of neurofilamentous pathology. *In* Neurofilaments. C. A. Marotta, editor. University of Minnesota Press, Minneapolis. 155–195.
30. Laemmli, U. K. 1970. Cleavage of structural proteins during the assembly of the head of bacteriophage T4. *Nature (Lond.).* 227:680–685.
31. Lane, E. B., and M. W. Klymkowsky. 1982. Epithelial tonofilaments: investigating their form and function using monoclonal antibodies. *Cold Spring Harbor Symp. Quant. Biol.* 46:387–402.
32. Liem, R. K. H., S. H. Yen, G. Salomon, and M. Shelanski. 1978. Intermediate filaments in nervous tissue. *J. Cell Biol.* 79:637–645.
33. Lin J. J.-C., and J. R. Feramisco. 1981. Disruption of the in vivo distribution of intermediate filaments in fibroblasts through the microinjection of a specific monoclonal antibody. *Cell.* 24:185–193.
34. Morris, N. R., M. H. Lai, and C. E. Oakley. 1979. Identification of a gene for α-tubulin in *Aspergillis nidulans*. *Cell.* 16:437–442.
35. Neff, N. F., J. H. Thomas, P. Grisafi, and D. Botstein. 1983. Isolation of the β-tubulin gene from yeast and demonstration of its essential function in vivo. *Cell.* 33:211–219.
36. Osborn, M., N. Geisler, G. Shaw, G. Sharpe, and K. Weber. 1982. Intermediate filaments. *Cold Spring Harbor Symp. Quant. Biol.* 46:413–429.
37. Pena, S. D. J. 1981. Giant axonal neuropathy: intermediate filament aggregates in cultured skin fibroblasts. *Neurology.* 31:1470–1473.
38. Pena, S. D. J. 1982. Giant axonal neuropathy: an inborn error of organization of intermediate filaments. *Muscle Nerve.* 5:166–172.
39. Pena, S D. J., M. Opas, K. Turksen, V. I. Kalnins, and S. Carpenter. 1983. Immunocytochemical studies of intermediate filament aggregates and their relationship with microtubules in cultured skin fibroblasts from patients with giant axonal neuropathy. *Eur. J. Cell Biol.* 34:227–234.
40. Peiffer, J., W. Scholte, A. Bishoff, E. Boltshauser, and G. Muller. 1977. Generalized giant axonal neuropathy—a filament-forming disease of neuronal, endothelial, glial and Schwann cells in a patient without kinky hair. *Acta Neuropathol.* 40:213–218.
41. Prineas, J. R., R. G. Ovrier, J. C. Wright, J. C. Walsh, and J. G. McLeod. 1976. Giant axonal neuropathy—a generalized disorder of cytoplasmic microfilament formation. *J. Neuropathol. Exp. Neurol.* 35:458–470.
42. Schliwa, M., and J. van Blerkom. Structural interaction of cytoskeletal components. *J. Cell Biol.* 90:222–235.
43. Seeds, N. W., A. G. Gilman, T. Amano, and M. W. Nirenberg. 1970. Regulation of axon formation in clonal lines of a neural tumor. *Proc. Natl. Acad. Sci. USA.* 66:160–167.
44. Seil, F. J., and J. Lampert. 1968. Neurofibrillary tangles induced by vincristine and vinblastine sulfate in central and peripheral neurons in vitro. *Exp. Neurol.* 21:219–230.
45. Sharpe, A. H., L. B. Chen, J. R. Murphy, and B. N. Fields. 1980. Specific disruption of vimentin filament organization in monkey kidney CV-1 cells by diptheria toxin, exotoxin A, and cycloheximide. *Proc. Natl. Acad. Sci. USA.* 77:7267–7271.
46. Sheir-Neiss, G., M. H. Lai, and N. R. Morris. 1978. Identification of a gene for β-tubulin in *Aspergillis nidulans*. *Cell.* 15:639–647.
47. Shortle, D., J. Haber, and D. Botstein. 1982. Lethal disruption of the yeast actin gene by integrative DNA transformation. *Science (Wash. DC).* 217:371–373.
48. Stein, G., and R. Yanishevsky. 1979. Autoradiography. *Methods Enzymol.* 58:279–295.
49. Thomas, G. P., W. J. Welch, M. B. Mathews, and J. R. Feramisco. 1982. Molecular and cellular effects of heat-shock and related treatments on mammalian tissue-culture cells. *Cold Spring Harbor Symp. Quant. Biol.* 46:985–996.
50. Toda, T., Y. Adachi, Y. Hiraoka, and M. Yanagida. 1984. Identification of the pleiotropic cell division cycle gene NDA2 as one of two different α-tubulin genes in *Schizosaccharomyces pombe*. *Cell.* 37:233–242.
51. Weber, K., and N. Geisler. 1982. The structural relation between intermediate filament proteins in living cells and the α-keratins of sheep wool. *EMBO (Eur. Mol. Biol. Organ.) J.* 1:1155–1160.
52. Wehland, J., and M. C. Willingham. 1983. A rat monoclonal antibody reacting specifically with the tyrosylated form of α-tubulin. II. Effects on cell movement, organization of microtubules, and intermediate filaments, and arrangements of golgi elements. *J. Cell Biol.* 97:1476–1490.