Growth Control in Cultured 3T3 Fibroblasts
II. Molecular Properties of a Fraction Enriched in Growth Inhibitory Activity

PETER A. STECK, JOHN BLENIS, PATRICIA G. VOSS, and JOHN L. WANG
Department of Biochemistry, Michigan State University, East Lansing, Michigan 48824

ABSTRACT
Treatment of sparse, proliferating cultures of 3T3 cells with medium conditioned by exposure to density-inhibited 3T3 cultures resulted in an inhibition of growth and division in the target cells when compared to similar treatment with unconditioned medium. This growth inhibitory activity was fractionated by ammonium sulfate precipitation and gel filtration, yielding one fraction that was 35-fold enriched in specific activity. Analysis of the chemical and biological properties of this highly active fraction indicated that: (a) it is an endogenous cell product, synthesized by the 3T3 cells and shed into the medium; (b) it is a protein and its activity is sensitive to treatment with pronase; (c) the constituent polypeptide chains have molecular weights of 10,000 and 13,000; and (d) it is not cytotoxic and its effect on target cells are reversible. These results suggest that we have partially purified from conditioned medium an endogenous growth regulatory factor that may play a role in density-dependent inhibition of growth in cultured fibroblasts. We propose the term Fibroblast Growth Regulator to describe this class of molecules.

The growth rate of normal cells in culture decreases as the number of cells approaches a critical cell density to form a monolayer. This phenomenon, which has been termed density-dependent inhibition of growth (1), was first described and most extensively studied in the 3T3 cell line (2, 3). From analysis performed in a number of laboratories, three major hypotheses have been proposed to account for density-dependent inhibition of growth. The first hypothesis suggests that cell-to-cell contact is a necessary requirement for growth inhibition (3, 4). A second hypothesis suggests that depletion of growth factors, in the bulk medium (5) or in a micro diffusion barrier surrounding the cells (6), causes the cessation of growth. The third hypothesis postulates that soluble growth inhibitors are released into the bulk medium and that these inhibitory factors accumulate to a sufficiently high concentration to act on the target cells.

Although these three theories are not mutually exclusive, several recent studies have provided evidence implicating the role of soluble inhibitory factors (7–10). For example, it has been demonstrated that growth and phosphate metabolism in sparse cultures of 3T3 cells were inhibited when the cells were placed in a petri dish containing dense cultures of the same cells (10). The ability of dense cultures of 3T3 cells to inhibit the proliferation of sparse cultures, separated from each other but sharing a common growth medium, suggests the depletion of medium or the presence of a soluble inhibitor as a possible mechanism for growth control in fibroblasts.

In a previous communication, we demonstrated that medium conditioned by exposure to cultures of density-inhibited 3T3 cells contained a growth inhibitory activity that acted on sparse, proliferating cultures of the same cell line (11). In this paper, we describe the isolation and characterization of a growth inhibitory fraction that yields two major protein components on polyacrylamide gel electrophoresis analysis. In addition, we demonstrate that the inhibitory activity is not cytotoxic and that its effects on cell growth are reversible. The results suggest that we have established a system for studying the mechanism of density-dependent growth control at the level of interactions of an endogenous growth inhibitor with its target cells.

MATERIALS AND METHODS
Cell Culture and Preparation of Conditioned Medium
Swiss 3T3 cells (American Type Culture Collection, Rockville, Md. CCL 92) were grown at 37°C in Dulbecco's modified Eagle's medium (DMEM) (K.C. Biological, Lenexa, Kans.) containing 10% calf serum (Microbiological Associates, Walkersville, Md.). The detailed protocol for the preparation of serum-free Condition Medium (CM(SF)) has been previously described (11). The following
and incubated for another 48 h. The cultures were then washed and stained. The cells were washed with PBS and were dissolved in 100 μl of 1% SDS. The cell number was then counted using an inverted microscope.

For experiments that required the source cells to be incubated with radioactive compounds, the labeled precursor was added to the medium during the production of CM(SF). The C-labeled precursors were added to a final concentration of 3.3 μCi/ml for [3H]thymidine (31.4 mCi/mmol, New England Nuclear, Boston, Mass.), [35S]methionine (68 mCi/mmol, Schwarz-Mann, Orangeburg, N. Y.), and to 5 μCi/ml for L-[3H]leucine amino acid mixture (1.87 mCi/mg, ICN Pharmaceuticals, Cleveland, Ohio). The [3H]Jmannose (20-30 mCi/mmol, New England Nuclear) was used at a final concentration of 1 mCi/ml. To prepare CM(SF) labeled with [35S]methionine, source cells were labeled with DMEM containing 3 μg/ml unlabeled methionine (one-tenth of the concentration normally found in DMEM) and 10 μCi/ml of [35S]methionine (1044 C/mml, New England Nuclear).

**Assays of Growth Inhibitory Activity**

Target cells were seeded at a density of 5 x 10^5 cells/cm² in a 24-well culture dish (2 cm²/well, Costar, Cambridge, Mass.) in DMEM containing 3 μg/ml unlabeled methionine and 10% calf serum. The cells were then incubated in [35S]methionine (1 μCi/well) for 24 h. The radioactive medium was then removed and the fraction (0.45 ml) was assayed for its growth inhibitory activity. This was done by placing the well along with 50 μl of calf serum. After 24 h, the cells were pulsed with 1 μCi/well of [3H]thymidine (1.9 C/mml, Schwarz-Mann) for 3 h at 37°C. The cells were then rinsed twice with cold PBS, once with 10% trichloroacetic acid (TCA), and then 0.55 ml of 1% sodium dodecyl sulfate (SDS) in 0.05 M NaOH was added. After incubation at 37°C for 10 min, an aliquot (0.3 ml) was removed and added to 5 ml of scintillation cocktail (21 g of 2,5-diphenyloxazole; 1 liter of Triton X-100; and 2 liters of toluene) containing 20 μl of 50% TCA. Autoradiographic analysis of cells labeled with [3H]thymidine was carried out as previously described (11).

The growth inhibitory activity of a CM-derived fraction was determined by comparing the amount of [3H]thymidine incorporation on a per cell basis in cultures treated with the fraction to the amount in UCM-treated cultures (percent inhibition, 100% — (CM/UCM) x 100). The number of cells in the target cultures treated with CM-derived fractions or with UCM was determined by the amount of [35S]methionine incorporated into the target cells before the treatments with the fractions to be tested for activity. It should be noted that because the CM(SF) was collected from [35S]-labeled cells, the CM-derived fractions that are added to the target cultures for tests of activity also contained radioactivity due to [35S] whereas the UCM control cultures did not. We have found, however, that the additional [35S] carried by the CM-derived fractions did not affect our determination of the number of target cells. This is mostly because the [35S] label carried by the CM-derived fractions was <5% of the level of [3H]radioactivity in the target cells and because much of this label could be removed by the PBS washing steps immediately after the [3H]thymidine incorporation.

**Assays of Cell Viability**

The viability of cells treated with UCM and CM was determined while the cells remained attached to the plastic growth surface. After removal of growth medium, the cells were incubated with trypan blue (0.08% in PBS) for 10 min at room temperature. The staining solution was then removed and the viable cells were counted using an inverted microscope.

Target cells were also labeled with 14C-amino acids (2 μCi/culture, 58 Ci/matoms of 14C, Amersham Corp., Arlington Heights, Ill.) for 24 h. After washing, these cells were treated with UCM(SF), CM(SF), or fractions derived from CM(SF) that contained growth inhibitory activity. At various times thereafter, the cells were washed with PBS and were dissolved in 100 μl of 2% SDS. The amount of labeled target cells remaining after the treatment with growth inhibitory was determined by counting the 14C radioactivity in each culture (11).

**Colony Formation Assay**

3T3 cells were seeded in a very sparse configuration (150 cells on 10 cm² of growth surface) in 35-mm dishes (Falcon Labware, Oxnard, Calif.). The cultures were incubated overnight to allow for cell attachment. The medium was then removed and parallel cultures were treated with 0.81 μl of UCMM(SF), CM(SF), or FGR-s fraction plus 0.09 ml of calf serum. After 48 h, the media were again removed and the cultures were refed with a fresh batch of corresponding media and incubated for another 48 h. The cultures were then washed and stained with 1% crystal violet (Sigma Chemical Co., St. Louis, Mo.) in 50% aqueous ethanol for 1 h. The cultures were washed three times with PBS. The number of colonies and the number of cells per colony were then counted under an inverted microscope.

**Fractionation and Gel Electrophoretic Analysis**

CM(SF) (60 ml) was precipitated by the addition of ammonium sulfate to a final concentration of 80% saturation. The precipitate, obtained after centrifugation at 12,400 g for 15 min, was redissolved in 1.5 ml of DMEM. Gel filtrations of the precipitated material were carried out at 4°C on a Sephadex G-50 column (90 x 1 cm) and a Sephadex G-15 column (27 x 1 cm) equilibrated with DMEM. Several different assays were carried out on the individual fractions from the columns. First, the inhibitory activity of each fraction was assayed on growing 3T3 target cells by measurements of [3H]thymidine incorporation. Second, 50-μl aliquots of each fraction were taken for the determination of total radioactivity. Third, the TCA-precipitable radioactivity, representing labeled macromolecular components, was determined by the addition of 100 μl of each fraction onto GF/A (Whatman) filters, washing twice with 10% TCA and then with absolute methanol. Finally, two different methods were used to determine the protein content of the fractions. In most experiments, the method described by Lowry et al. (12) was used, with bovine serum albumin as a calibration standard. In some experiments, the much more sensitive method of Schaffner and Weissman (13) was used, with ribonuclease A as a standard.

Protein fractions were labeled with 35S using the method of Greenwood et al. (14). After the labeling reaction, noncovalently bound 35S was removed by gel filtration on a column (38 x 2 cm) of Bio-Gel P-2 (Bio-Rad Laboratories, Richmond, Calif.) equilibrated with PBS.

Polyacrylamide gel electrophoresis in SDS was performed according to the procedure of Laemmli (15), using 10% or 15% acrylamide running gels and 5% acrylamide stacking gel. β-Mercaptoethanol (4%) was included in the sample buffer. The gels were fixed and then stained with Coomassie Brilliant Blue. After destaining, the gel was subjected to fluorographic treatment as described by Bonner and Laskey (16), using Kodak X-Omat RFP (XR-S) film. Alternatively, the gels were sliced immediately after electrophoresis, solubilized by digestion with 30% hydrogen peroxide (60° for 5 h), and then subjected to scintillation counting.

In certain gels containing 35S-labeled samples, direct autoradiography was performed instead of fluorography; Kodak X-Omat RFP (XR-S) film and intensification screens were used in these autoradiographic procedures.

**Sensitivity of Growth Inhibitory Activity to Hydrolytic Enzymes**

The sensitivity of the growth inhibitory activity to various enzymes was tested using proteases and nucleases coupled to solid supports. Pronase coupled to carboxymethyl-cellulose beads and ribonuclease A bound to polyacrylamide beads were purchased from Sigma Chemical Co. Bovine deoxyribonuclease I (Worthington Biochemical Corp., Freehold, N. J.) coupled to Sepharose beads was prepared according to the method of Lazarides and Lindberg (17).

All enzyme digestion experiments were carried out in pyrex, siliconized test tubes precoated with BSA to minimize nonspecific adsorption of the proteins to the glass surface. The tubes were incubated with BSA (2 mg/ml) for 1 h at 37°C. They were then washed two times with PBS and three times with DMEM. For the pronase-bead experiments, 0.40 ml of UCM(SF), CM(SF), or FGR-s was added to tubes containing 0.06 U of enzyme, and the mixtures were incubated at 37°C for up to 18 h. The highest concentrations tested for ribonuclease-beads and deoxyribonuclease-beads were 0.01 U/ml and 0.014 U/ml, respectively.

After the incubation, the reaction mixtures were centrifuged at 1470 g for 5 min and the supernatant was removed from the pelleted beads for tests of growth inhibitory activity and for gel electrophoretic analysis. These procedures, allowing us to effectively remove the hydrolytic enzymes after the reaction period, have observed the many problems associated with the addition of proteases and/or protease inhibitors to the target cells, which in turn often changed the proliferative properties of the cells.

**RESULTS**

**Fractionation of the Growth Inhibitory Activity in Conditioned Medium**

We have reported previously the optimized parameters for the collection of CM(SF) from source cells and for the assay of the growth inhibitory activity on target cells (11). We have now carried out fractionation of the growth inhibitory activity using ammonium sulfate precipitation and gel filtration on a column of Sephadex G-50 (Fig. 1). In these experiments, CM(SF) was
The data represent the averages of triplicate determinations of trichrom (1,400) min (68,000), myoglobin (17,000), ribonuclease T (11,000), and bacitracin (1,400).

The growth inhibitory activity of the ammonium sulfate precipitate fraction was assayed at various stages of the fractionation protocol. The growth inhibitory activity of CM-derived fractions is expressed as percent inhibition of DNA synthesis due to 1 ml of the fractionated material. Percent inhibition is defined as the amount of [3H]thymidine incorporation on a per cell basis in cultures treated with CM-derived fractions as compared to UCM-treated cultures. The number of cells in the target cultures treated with CM-derived fractions and with UCM is determined by the amount of [35S]methionine incorporated into the target cells before the treatments with the fractions to be tested for activity. Total activity is calculated by multiplying the percent inhibition of the fraction by the total volume of the fraction.

The growth inhibitory activity of CM-derived fractions is expressed as percent inhibition of DNA synthesis due to 1 ml of the fractionated material. Percent inhibition is defined as the amount of [3H]thymidine incorporation on a per cell basis in cultures treated with CM-derived fractions as compared to UCM-treated cultures. The number of cells in the target cultures treated with CM-derived fractions and with UCM is determined by the amount of [35S]methionine incorporated into the target cells before the treatments with the fractions to be tested for activity. Total activity is calculated by multiplying the percent inhibition of the fraction by the total volume of the fraction.

The growth inhibitory activity of CM-derived fractions is expressed as percent inhibition of DNA synthesis due to 1 ml of the fractionated material. Percent inhibition is defined as the amount of [3H]thymidine incorporation on a per cell basis in cultures treated with CM-derived fractions as compared to UCM-treated cultures. The number of cells in the target cultures treated with CM-derived fractions and with UCM is determined by the amount of [35S]methionine incorporated into the target cells before the treatments with the fractions to be tested for activity. Total activity is calculated by multiplying the percent inhibition of the fraction by the total volume of the fraction.

The growth inhibitory activity of CM-derived fractions is expressed as percent inhibition of DNA synthesis due to 1 ml of the fractionated material. Percent inhibition is defined as the amount of [3H]thymidine incorporation on a per cell basis in cultures treated with CM-derived fractions as compared to UCM-treated cultures. The number of cells in the target cultures treated with CM-derived fractions and with UCM is determined by the amount of [35S]methionine incorporated into the target cells before the treatments with the fractions to be tested for activity. Total activity is calculated by multiplying the percent inhibition of the fraction by the total volume of the fraction.

The growth inhibitory activity of CM-derived fractions is expressed as percent inhibition of DNA synthesis due to 1 ml of the fractionated material. Percent inhibition is defined as the amount of [3H]thymidine incorporation on a per cell basis in cultures treated with CM-derived fractions as compared to UCM-treated cultures. The number of cells in the target cultures treated with CM-derived fractions and with UCM is determined by the amount of [35S]methionine incorporated into the target cells before the treatments with the fractions to be tested for activity. Total activity is calculated by multiplying the percent inhibition of the fraction by the total volume of the fraction.
(3 h). In contrast, the fractions of labeled nuclei in cultures treated with CM-derived fractions were significantly lower. The percent inhibition observed for CM(SF) and for components A and C (Fig. 1) were 33%, 19%, and 26%, respectively. Therefore, the inhibition of [3H]thymidine incorporation into target cells treated with CM-derived fractions reflects a true reduction of the percent of cells undergoing DNA synthesis rather than alterations of the transport or pool sizes of the label.

Gel Electrophoretic Analysis and Identification of the Polypeptides Associated with the Growth Inhibitory Activity

The materials containing growth inhibitory activity at various stages of fractionation were subjected to polyacrylamide gel electrophoresis in SDS. After electrophoresis, the gel was stained with Coomassie Blue; in addition, the gel was subjected to fluorography to reveal 35S-labeled protein components. The gel revealed a large number of proteins, as detected by Coomassie Blue staining and by fluorography, for CM(SF), ammonium sulfate precipitate and component A (Fig. 1 a) from the Sephadex G-50 column (lanes 1-3, Fig. 2 a and b). In contrast, component C (Fig. 1 a) yielded no Coomassie Blue-positive material (lane 5, Fig. 2 a) and only two major bands on the fluorogram (lane 5, Fig. 2 b). Identical results were obtained in the presence and absence of β-mercaptoethanol during the electrophoresis. The mol wt estimated for the two bands (lane 3, Fig. 2 b) in component C (Fig. 1 a) were 10,000 and 13,000. These results suggest that, under both gel filtration and SDS gel electrophoresis conditions, the two polypeptides migrate without any evidence of covalent linkage to each other.

The experiment described above used CM(SF) material derived from six flasks of 3T3 source cells. When the experiment was scaled up 10-fold, the pooled material corresponding to component C (Fig. 1 a) yielded two Coomassie Blue-stained bands on polyacrylamide gel electrophoresis (Fig. 3). The electrophoretic mobilities of these polypeptides were identical to those of the labeled bands (Mr: 10,000 and Mr: 13,000).

Densitometric analysis of the fluorogram of component C (lane 5, Fig. 2 b) indicated that the two bands accounted for 98% of the radioactive material in the gel. In addition, a parallel experiment was carried out in which the gel sample was not fixed and stained but was sliced into fractions immediately after electrophoresis. These fractions were then solubilized and subjected to scintillation counting (Fig. 4). More than 97% of the radioactivity was recovered in the gel slices corresponding to the two bands observed in the fluorogram of component C (lane 5, Fig. 2 b). This result argues against the possibility that low mol wt components, representing major contaminants, could have diffused from the gel during the fixation and staining procedures and, therefore, would have escaped detection in the fluorogram.

Finally, the material in component C was labeled with 125I and subjected to gel electrophoretic analysis. It was found that 98% of the radioactivity was associated with two bands (Fig. 5), corresponding to those observed in the gels of the 35S-labeled sample (lane 5, Fig. 2 b). This result suggests that there was no other protein species in component C that was previously undetectable by Coomassie Blue staining or [35S]methionine labeling. All of these results, coupled with the data shown in Table I, strongly suggest that component C represents a highly purified preparation enriched in terms of specific activity. At present, we do not have any information on whether the two bands in component C (Fig. 1 a) constitute a single activity for growth inhibition or whether they are in any way related. Therefore, it is possible that only one of the polypeptides is responsible for the bioactivity. With this qualification in mind, we shall hereafter refer to this material (component C, Fig. 1 a) as Fibroblast Growth Regulator—soluble form (FGR-s).

Chemical Characterization of FGR-s

Although we have identified the polypeptide chains associated with FGR-s, the question of whether other chemical components may be associated with the inhibitory activity remained to be addressed. To determine the composition of the purified inhibitory fraction, parallel cultures of source cells were grown in the presence of 14C-labeled amino acids, thymidine, uridine, and d-[2-3H]mannose. When CM(SF) was prepared from source cells prelabeled with 14C-amino acids...
and then fractionated, we found $^{14}$C radioactivity in the fractions corresponding to components A and C (Fig. 1a) in the elution profile of the Sephadex G-50 column (Fig. 6a). These results corroborate the data obtained using the $^{35}$S methionine label.

In contrast to these findings, collection of CM(SF) from source cells prelabeled with $^{14}$C thymidine or $^{14}$C uridine did not yield any radioactive components corresponding to the FGR-s fractions (Fig. 6c and d). These results suggest that there were no DNA or RNA molecules associated with the inhibitory activity. This conclusion was further corroborated by experiments in which the sensitivity of the growth inhibitory activity to various enzymes was tested.

To carry out these experiments, pronase was first immobilized on beads. The enzyme-bead complexes were then incubated with the fractions to be tested for enzyme sensitivity. After the incubation, the reaction mixtures were centrifuged and the supernatant was removed from the pelletted beads for tests of growth inhibitory activity on target cells and for gel electrophoresis. Incubation of FGR-s fraction with pronase-beads followed by gel electrophoretic analysis showed a decrease in the intensity of the radioactive bands ($M_c$: 10,000 and $M_c$: 13,000). This was paralleled by loss of growth inhibitory activity. After 18 h of incubation, no activity was detectable in our assay system (Fig. 7). In contrast, the activity was not affected by treatment with deoxyribonuclease-beads and ribonuclease-beads. Thus, the results of these enzyme sensitivity experiments provide data confirmatory to those obtained in experiments using radioactively-labeled precursors.
When CM(SF) was collected from source cells cultured for 24 h in the presence of d-[2-3H]mannose, fractionation on the Sephadex G-50 column yielded radioactive only in fractions corresponding to component A (Fig. 6b). No radioactivity was detected in fractions corresponding to component C, even when the incubation medium contained as much [2-3H]mannose as 1 mCi/ml. We have not tested as yet other precursors for labeling glycoproteins such as l-[14C]fucose or d-[14C]-glucosamine.

The Effects of FGR-s on Target Cells: Dose-response, Viability and Reversibility

The inhibitory effect of FGR-s on [3H]thymidine incorporation in target cells was dependent on the concentration of ligand added (Fig. 8). Above 100 ng/ml, there was a monotonic increase in inhibitory activity with increasing concentration of FGR-s added to the cultures. The concentration of inhibitor required for 50% inhibition was ~400 ng/ml. At the highest concentration tested (720 ng/ml), the percent inhibition achieved was ~60%. We have recently demonstrated the binding of [35S]methionine-labeled FGR-s to target 3T3 cells; the growth inhibitory effect of increasing concentrations of FGR-s paralleled the increase in the amount of binding observed.

Three series of experiments were performed to ascertain that the inhibition of [3H]thymidine incorporation in target cells by FGR-s was due to a true suppression of cell growth rather than to any cytotoxic effects of the inhibitory fractions. First, the viabilities of the cells, assayed by the trypan blue exclusion tests, were identical for target cultures treated with FGR-s and with UCM(SF) for up to 48 h. Because nonviable cells could have been lost from the dishes, we prelabeled the target cells by culturing them in the presence of [14C]-amino acids. After treatment with FGR-s for 24 and 48 h, the levels of [14C] label retained were found to be similar to those observed for control cultures (Fig. 9). The same results were also obtained when target cells were treated with CM(SF) and UCM(SF).

In another series of experiments, 3T3 cells were seeded onto culture dishes in a very sparse configuration such that individual cells would give rise to colonies. After overnight incubation, the medium was removed and parallel cultures were treated with UCM(SF), CM(SF), and FGR-s for 96 h. When the number of cells in each colony and the number of colonies were counted, the control culture (UCM(SF)) showed a population distribution ranging from 10 cells per colony to 150 cells per colony (Fig. 10a). The average numbers of cells per colony was 72. In contrast, when the sparsely distributed cells were treated with CM(SF) or isolated FGR-s fraction, the number of colonies with fewer than 50 cells per colony increased significantly and the distributions were centered around mean values of 44 and 48, respectively (Fig. 10b and c).

Student's t tests were used to compare the means of the distributions shown in the histograms of Fig. 10. The mean values for the distributions of UCM(SF) and CM(SF) were significantly different (t = 6.17, df = 227, P < 0.0001). Similarly, the mean values for UCM(SF) and FGR-s were significantly different (t = 5.02, df = 246, P < 0.0001). In contrast, the mean values for CM(SF) and FGR-S showed significant

---

1 Voss, P. G., P. A. Steck, J. C. Calamia, and J. L. Wang. Growth control in cultured 3T3 fibroblasts. III. Binding interactions of a growth inhibitory activity with target cells. Exp. Cell Res. In press.
decreasing the size of the colonies without affecting the overall viability of target cells was not affected by FGR-s, these results suggest that the inhibitory activity of FGR-s cannot be ascribed to cytotoxicity.

FIGURE 10. Cell count distributions for colonies of 3T3 cultures treated with (a) UCM(SF), (b) CM(SF), and (c) FGR-s. The following numerical data were obtained: (a) UCM(SF), 137 total colonies counted, average number of cells per colony, 72; (b) CM(SF), 138 total colonies counted, average number of cell per colony, 44; and (c) FGR-s, 133 total colonies counted, average number of cells per colony, 48. In d, the data of panels a–c are plotted in the form of a cumulative distribution curve of colony size. (O) UCM(SF) cultures, (O) CM(SF) cultures, (X) FGR-s cultures.

similarity (r = 1.29, df = 268, P > 0.2). A similar conclusion can be derived from a plot of the cumulative distribution of colony size (Fig. 10d). For example, 70% of the colonies in cultures treated with CM(SF) or FGR-s had 50 cells or less whereas the corresponding value for UCM(SF)-treated cultures was 30%.

Most importantly, we have found that there was no difference in the total number of colonies in dishes treated with UCM(SF), CM(SF), or FGR-s. All of these results suggest that CM(SF) and FGR-s inhibited the growth of cells, thereby decreasing the size of the colonies without affecting the overall number of the originally attached cells. Moreover, the data provide a confirmation of the growth inhibitory activity of FGR-s using an assay that is independent of [3H]thymidine incorporation.

To demonstrate that the inhibitory effect of FGR-s on DNA synthesis was reversible, parallel target cultures were treated with FGR-s for 24 h. The medium was then removed and replaced with an equal volume of fresh growth medium. At various times thereafter, DNA synthesis was assayed by the incorporation of [3H]thymidine. The data showed that the inhibition was reversible within 20 h after removal of FGR-s (Table II). Taken together with the demonstration that the viability of target cells was not affected by FGR-s, these results suggest that the inhibitory activity of FGR-s cannot be ascribed to cytotoxicity.

| Conditions | 24 h* | 12 h after reversal‡ | 24 h after reversal§ |
|------------|-------|----------------------|----------------------|
| CM(SF)     | 56    | 105                  | 125                  |
| FGR-s      | 54    | 130                  | 127                  |

* Target cells (5 x 10^3 cells/cm²) were treated for 24 h with CM-derived and UCM fractions. DNA synthesis was then measured by the incorporation of [3H]thymidine. The results are expressed as percent of control ([3H]thymidine incorporated in cultures treated with CM-derived fractions divided by [3H]thymidine incorporation in UCM cultures).

‡ After the cultures were treated for 24 h with CM-derived or UCM fractions, the medium was removed and replaced by an equal volume of fresh growth medium. DNA synthesis in these cultures was measured 12 h and 24 h later.

DISCUSSION

The results obtained in the present study indicate that we have partially purified, from the 3T3 fibroblast system, a growth inhibitory preparation enriched in specific activity. This preparation has the following key properties: (a) it is an endogenous cell product, synthesized by the 3T3 cells and shed into the medium; (b) it is a protein and its activity is sensitive to treatment with pronase; (c) the constituent polypeptide chains have mol wt of 10,000 and 13,000; and (d) it is not cytotoxic to the target cell and its effects on cell growth are reversible. We have also obtained evidence that at least one of these two polypeptides (Mₚ: 10,000) is stably bound by the 3T3 target cells. Although it is still possible that the growth inhibitory activity is due to molecules present in minute amounts well below our detection levels, the best candidates for this activity appear, at the present, to be these two protein components. We propose to designate this factor FGR-s, which stands for Fibroblast Growth Regulator that is secreted or shed into the medium in a soluble form.

Growth inhibitory factors have also been studied in a number of other cultured cells that exhibit density-dependent inhibition of growth. Lipkin and Knecht have reported that a glycoprotein of mol wt 160,000 can be isolated from culture medium of contact-inhibited hamster melanocytes and that this factor can reversibly inhibit growth in vitro of a broad spectrum of malignant and normal cell types of ectodermal, mesodermal and endodermal origins (19–21). Moreover, an electrophoretically identical protein has been found in culture media of contact-inhibited fibroblasts and epidermal cells.

Holley and co-workers have reported (22) that the growth of the monkey epithelial cell line, BSC-1, is limited at high cell densities partly by the action of three inhibitors. Two of these inhibitors have been isolated from the culture medium of BSC-1 cells (23). At ng/ml concentrations, they reversibly arrest the growth of the same cells in the G1 phase of the cell cycle. On the basis of the chromatographic behavior on Bio-Gel P-60 columns, the molecular weight of one of these inhibitors was estimated to be ~15,000.

Our most highly purified preparation of FGR-s yielded two major protein components on polyacrylamide gel electrophoresis in SDS (Mₚ: 10,000 and Mₚ: 13,000, panel 5, Fig. 2b). The growth inhibitory activity of this material may be due to (a) one of the polypeptides acting alone; (b) both of the polypeptides acting independently; or (c) a complex of the two polypeptides associated together, either one of which is not sufficient for activity. The resolution of these possibilities must await the successful separation of these two components under non-denaturing conditions so that the activity of each polypeptide and the reconstituted system can be compared.
Moreover, we have yet to determine the relationship of the two polypeptides to each other. For example, one (M, 10,000) may be a fragment derived from the other (M, 13,000). In this connection, it is also possible that one or both of the polypeptides in component C (Fig. 1) represent proteolytic products of larger precursors observed in component A (Fig. 1). This hypothesis is supported by preliminary experiments which indicate that prolonged incubation of CM(SF) at 37°C followed by chromatography on Sephadex G-50 generated more material eluting in the molecular weight range of component C (Fig. 1).

The possibility of a higher molecular weight precursor form of the FGR-s polypeptides may be particularly important in considering the biological significance of the isolated inhibitor fraction. It should be emphasized that the highest level of inhibition obtained with the FGR-s fraction is ~60%. Therefore, the proliferation of the target cells is not completely suppressed by the presence of the inhibitor. Similarly, the results of the colony formation assays indicate that, despite significant reductions in the size of the colonies, the presence of the FGR-s fraction still allowed some cell growth and division to occur. Finally, we have estimated that over 15 h, a time-period required for accumulation of appreciable activity in CM (11), each source cell yielded 1 pg of the FGR-s fraction and that, under such production rates, at least 30–40 source cells were required to inhibit one target cell. These estimates are obviously incomplete inasmuch as we have yet to take into account other variables such as: (a) the density-dependence of target cells in response to the inhibitory activity; (b) the degradation rate of the isolated activity; and (c) the presence of inhibitory activity in peak A (Fig. 1) of the preparation. All these considerations call for caution in interpreting the absolute significance of the isolated FGR-s as a growth regulatory factor and suggest that perhaps higher molecular weight precursors or membrane-bound forms of the molecule may yield higher levels of growth inhibition.

These considerations also emphasize the limitations of the inhibitor concept as a complete explanation for density-dependent inhibition of growth in cultured cells. As we had discussed previously (11), many laboratories have contributed evidence in support of three major hypotheses accounting for the phenomenon of density-dependent inhibition of growth: (a) cell-to-cell contact effects; (b) depletion of growth stimulatory factors; and (c) release of soluble inhibitors. These three mechanisms are not mutually exclusive and may in fact be synergistic with each other. Thus, the isolated FGR-s fraction of our present study may act in direct antagonism with growth stimulatory factors or in concert with cell contact effects.

In this connection, Whittenberger and Glaser have shown that the growth of 3T3 cells can be reversibly inhibited by a surface membrane fraction from the same cells (24) and that the inhibitory components can be solubilized by the nonionic detergent octylglucoside (25). Natraj and Datta have also shown that an inhibitor of DNA synthesis can be extracted from 3T3 cells by treatment with 0.2 M urea in PBS (26, 27). It was suggested that these surface membrane molecules which inhibit cell proliferation may be the same molecules that are responsible for contact-dependent growth regulation.

In both of these studies on the membrane-bound growth regulatory factor(s), no purified preparation of the inhibitory molecule has, to date, been reported. It would be of obvious interest to establish the relationship between the FGR-s from CM and the similar activity observed in the membrane fractions. It is possible, for example, that the same molecule can exert its effects either anchored on the cell surface or released into the medium. The isolation of FGR-s and the characterization of its polypeptide chains represent the first step in the parallel lines of experiments on membrane-bound and soluble forms of growth regulatory factors that mediate density-dependent inhibition of growth.

We thank Drs. C. C. Sweeney and A. J. Morris for helpful suggestions and for critically reading this manuscript. We also wish to thank J. A. Voss for his help in the statistical analysis of the data on colony formation.

This work was supported by grants from The American Cancer Society (BC-277A), the National Institutes of Health (GM-27203), and The Thresher Research Fund. J. L. Wang was supported by Faculty Research Award FRA-221 from The American Cancer Society.

Received for publication 29 July 1981, and in revised form 24 September 1981.

REFERENCES

1. Stoker, M. G. P., and H. Rubin. 1967. Density-dependent inhibition of cell growth in culture. Nature (Lond.) 215:171-172.
2. Todaro, G. J., and H. Green. 1965. Quantitative studies of the growth of mouse embryo cells in culture and their development into established lines. J. Cell Biol. 27:399-311.
3. Todaro, G. J., and H. Green. 1966. Transformation of properties of an established cell line by SV 40 and polyoma virus. Proc. Natl. Acad. Sci. U. S. A. 51:66-76.
4. Todaro, G. J., G. K. Lazar, and H. Green. 1965. The initiation of cell division in a contact-inhibited mammalian cell line. J. Cell. Comp. Physiol. 60:325-334.
5. Holley, R. W., and J. A. Kiyman. 1968. "Contact inhibition" of cell division of 3T3 cells. Proc. Natl. Acad. Sci. U. S. A. 60:300-304.
6. Stoker, M. G. P. 1973. Role of diffusion boundary layer in contact inhibition of growth. Nature (Lond.) 242:200-203.
7. Rheinstaudt, J. G., and H. Green. 1975. Formation of a keratinizing epithelium in culture by a cloned cell line derived from a teratoma. Cell 6:317-330.
8. Canagaratna, M. C. P., and P. A. Riley. 1975. The patterns of density-dependent growth inhibition in murine fibroblasts. J. Cell. Physiol. 85:271-282.
9. Harrel, L., and M. Jullien. 1976. Evaluation of proximity inhibition of DNA synthesis in 3T3 cells, J. Cell. Physiol. 88:233-254.
10. Harrel, L., M. Jullien, and M. DeMente. 1978. Diffusible factor(s) controlling density-dependent inhibition of 3T3 cell growth: a new approach. J. Cell. Physiol. 96:327-332.
11. Steck, P. A., P. G. Voss, and J. L. Wang. 1979. Growth control in cultured 3T3 fibroblasts. Assays of cell proliferation and demonstration of a growth inhibitory activity. J. Cell. Biol. 83:562-575.
12. Lowry, O. H., N. J. Rosebrough, A. L. Farr, and R. J. Randall. 1951. Protein measurement with the Folin phenol reagent. J. Biol. Chem. 193:265-275.
13. Schaffner, W., and C. Weissman. 1973. A rapid, sensitive, and specific method for the determination of protein in dilute solution. Anal. Biochem. 56:502-514.
14. Hunter, W. M., and E. C. Greenwood. 1962. Preparation of 3H-labeled growth hormone of high specific activity. Nature (Lond.) 194:849-856.
15. Laemmli, U. K. 1970. Cleavage of structural proteins during the assembly of the head of bacteriophage T4. Nature (Lond.) 227:680-686.
16. Bonner, W. M., and R. A. Lasker. 1974. A film detection method for tritium-labeled proteins and nucleic acids in polyacrylamide gels. Exp. J. Biochem. 46:83-88.
17. Lazarides, E., and U. Lindberg. 1974. Actin is the naturally occurring inhibitor of decortylylbenzamide I. Proc. Natl. Acad. Sci. U. S. A. 71:4742-4746.
18. Paul, D., K. D. Brown, H. T. Ruprich, and H. J. Risow. 1978. Cell cycle regulation by growth factors and nutrients in normal and transformed cells. In Vitro (Rockville). 14:76-86.
19. Lipkin, G., and M. E. Knecht. 1974. A diffusible factor reconstituting contact inhibition of growth to malignant melanocytes. Proc. Natl. Acad. Sci. U. S. A. 71:849-853.
20. Knecht, M. E., and G. Lipkin. 1977. Biochemical studies of a protein which restores contact inhibition of growth to malignant melanocytes. Exp. Cell Res. 108:15-22.
21. Lipkin, G., M. E. Knecht, and M. Rosenberg. 1978. A potent inhibitor of normal and transformed cell growth derived from contact-inhibited cells. Cancer Res. 38:635-643.
22. Holley, R. W., R. Armon, and J. H. Baldwin. 1978. Density-dependent regulation of growth of BSC-1 cells in cell culture: growth inhibitors formed by the cells. Proc. Natl. Acad. Sci. U. S. A. 75:1864-1866.
23. Holley, R. W., R. Fabb, J. H. Baldwin, G. Klemes, and R. Armon. 1980. Purification of kidney epithelial cell growth inhibitors. Proc. Natl. Acad. Sci. U. S. A. 77:5999-5992.
24. Whittenberger, B., and L. Glaser. 1977. Inhibition of DNA synthesis in cultures of 3T3 cells by intact surface membranes. Proc. Natl. Acad. Sci. U. S. A. 74:2231-2235.
25. Whittenberger, B., D. Ruben, M. A. Lieberman, and L. Glaser. 1978. Inhibition of growth of 3T3 cells by extract of surface membranes. Proc. Natl. Acad. Sci. U. S. A. 75:5477-5481.
26. Natraj, C. V., and P. Datta. 1978. Control of DNA synthesis in growing Balb/c 3T3 mouse cells by a fibroblast growth regulatory factor. Proc. Natl. Acad. Sci. U. S. A. 75:6115-6119.
27. Datta, P., and C. V. Natraj. 1980. Fibroblast growth regulatory factor inhibits DNA synthesis in Balb/c 3T3 cells by arresting in G1. Exp. Cell Res. 125:431-439.