# Multiple Controls for the Synthesis of Muscle-specific Proteins in $BC_3H1$ Cells

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ABSTRACT The regulation of the synthesis of muscle-specific proteins has been examined in $BC_3H1$ cells, a smooth muscle-like cell line isolated by Schubert et al. (*J. Cell Biol.*, 1974, 61: 398–413.). The synthesis of both creatine kinase and the acetylcholine receptor appear to be under dual control, a positive control due to cell-cell contact which increases the rate of synthesis of this protein, and a negative signal, elicited by serum components, that decreases the rate of synthesis of these proteins. Induction of muscle-specific proteins in $BC_3H1$ cells is a reversible process and can be arrested after partial induction has taken place by the addition of serum or high-molecular-weight protein fraction from serum to these cells. The high-molecular-weight protein fraction from serum is not by itself mitogenic for $BC_3H1$ cells and cannot be replaced by a variety of known hormones (mitogenic factors).

The control of the synthesis of specific proteins during myogenesis has been the subject of intensive investigation in various tissue culture systems using myoblasts or established cell lines such as L-6 (1, 17, 20). Most of these systems use fusing cells, where the events related to cell fusion cannot always be readily separated from the cell recognition events necessary for the induction of muscle-specific proteins (such as creatine kinase and the acetylcholine receptor) (2, 7, 19, 21). Less information is available regarding the induction of muscle-specific proteins in smooth muscle cells (5). $BC_3H1$ is a smooth-muscle-like cell line isolated several years ago by Schubert et al. (18). These cells do not fuse but induction of the synthesis of the muscle isoenzyme of creatine kinase and the acetylcholine receptor can be demonstrated to take place under a variety of conditions (13, 18).

In this communication we present evidence to show that in these cells the synthesis of muscle-specific proteins is regulated by the balance between two antagonistic signals: cell contact brings about the induction of the synthesis of these proteins whereas serum factors suppress the induction of these proteins. Induction of these muscle-specific proteins is a reversible phenomenon. While induction of these muscle-specific proteins only occurs in quiescent cells, repression (inhibition of induction) is not obligatorily coupled to the resumption of cell growth.

## MATERIALS AND METHODS

$BC_3H1$ cells, a nonfusing muscle cell line, was obtained from Dr. D. Schubert at the Salk Institute. The cells were grown at 37°C in a 10% $CO_2$-enriched atmosphere in Dulbecco's modified Eagle's medium (DMEM) supplemented, where indicated, with 15% nutrient medium F12 and the specified concentration of dialyzed fetal calf serum or dialyzed horse serum and L-glutamine (0.1 mg/ml), penicillin (0 U/ml), and streptomycin (100 μg/ml). Cells were transferred from log phase cultures by trypsinization with crystalline trypsin, and replated. Fresh cultures were started from frozen stock at 4- to 6-wk intervals. Media were obtained from Gibco Laboratories (Grand Island Biological Co., Grand Island, NY) or the Washington University Basic Cancer Center. Sera were obtained from Gibco Laboratories and K. C. Biologicals.

In some experiments cells were grown on collagen-coated dishes. Dishes were coated by $NH_3$ vapor precipitation of acid-soluble calf skin collagen (Sigma Chemical Co., St. Louis, MO) (14). The dishes were stored dry after sterilization with UV light. Before use, dishes were washed twice with Hepes-buffered $Ca^{++}$- and $Mg^{++}$-free Hanks' solution and once with complete medium.

Creatine kinase was determined by the following modification of published procedures (11, 20). Cultures in 35-mm dishes were washed once with 2 ml of phosphate-buffered saline (PBS) and the cell layer was suspended in 0.5 ml of 1% nonidet P-40 (NP-40) in 50 glycyl-glycine, pH 6.75. The cells were homogenized (10 to 15 strokes) in a 1-ml Dounce homogenizer. For assay, the extract was appropriately diluted in the same buffer containing 1 mg/ml bovine serum albumin (BSA).

A two-stage assay for creatine kinase is used. In the first stage, the reaction mixture contains 1 mM ADP, 10 mM $MgCl_2$, 0.2% BSA, 0.1 mM $P^1,P^5$ diadenosine, 5′ pentaphosphate (Boehringer Mannheim Biochemicals, Indianapolis, IN), 2.5 mM dithiothreitol, 25 mM phosphocreatine, 3 mM D-glucose and 20 U/ml hexokinase, and extract in a total volume of 40 μl. Controls lack phosphocreatine. The reaction is initiated by the addition of extract. After incubation at 37°C for 30 min, the reaction is stopped by the addition of 10 μl of 1 N NaOH. After incubation at 25°C for 10 min, the reaction mixture is diluted to 0.8 ml with 50 mM imidazole buffer, pH 7.0, followed by the addition of NADP and glucose 6-P-dehydrogenase to a final concentration of 0.82 mM and 1.07 U/ml, respectively, in a total volume of 1 ml. After incubation at 25° for 10 min, the fluorescence due to NADPH is determined in a Farrand Fluorimeter (11), and values obtained in the absence of phosphocreatine were subtracted. The assay is linear with time, and up to 10 nmol of NADPH formed during the assay period.



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At least two concentrations of each extract were tested to insure linearity, and all results are the average of duplicate dishes. Creatine kinase was normalized to cell numbers determined in duplicate dishes with a Coulter counter or to cell protein obtained by growing cells for a minimum of two generations in medium supplemented with radioactive amino acid usually with 1 μCi/ml of [$^3$H]-leucine, and measuring the radioactivity in protein by precipitation with trichloroacetic acid in the presence of deoxycholate (15) in the same extracts as were used for the assay of creatine kinase. Although both protein and cell number were determined in each experiment, the results were always identical; therefore, in most experiments we present only the data based on cell numbers. All reagents, unless otherwise indicated, were obtained from Sigma Chemical Co. It is important that the ADP used be as free of ATP as possible.

The acetylcholine receptor was determined by measuring the binding of [$^{125}$I]α-bungarotoxin (13). α-Bungarotoxin (Sigma Chemical Co.) was iodinated using immobilized lactoperoxidase (Bio-Rad Enzymobeads; Bio-Rad Laboratories, Richmond, CA); the specific activity of the labeled toxin preparations used averaged 25 μCi/μg. Nonspecific binding was determined in the presence of 1 carbamylcholine. 0.1 μg of [$^{125}$I]α-bungarotoxin was added directly to 35-mm culture dishes, which were then incubated for 50 min at 37°C. Control dishes received carbamylcholine (1 mM final concentration) 10 min before the addition of α-bungarotoxin. At the end of the incubation, the dishes were subjected to six rapid washes with 2 ml of DME containing 2% horse serum. The cell layer was solubilized in 2 ml of 1% SDS (in PBS) and counted in a Beckman gamma counter (Beckman Instruments, Inc., Fullerton, CA).

Fetal calf serum (Gibco Laboratories, Lot C688209) was fractionated at 4°C as follows. The serum was dialyzed overnight against 10 vol of 0.1 M Tris-Cl, pH 7.4. 50 ml of dialyzed serum was applied to a 2.4 × 20-cm column of CM-Sephadex C-50 equilibrated with the same buffer. Serum proteins were eluted from the column with the same buffer until the $OD_{280\ nm}$ was below 0.6 (16). The eluate was concentrated to the original volume, using a Pellicon PTGC 10,000 molecular weight exclusion filter (Millipore Corp., Bedford, MA) in an Amicon concentrator (Amicon Corp., Lexington, MA), and dialyzed against PBS. 20-ml aliquots were applied to a 2.5 × 137-cm Sephacryl S-200 column equilibrated with PBS. The sample was eluted at a flow rate of 0.53 ml/min. 5.3-ml fractions were collected and pooled and concentrated as indicated in Fig. 9 (see below). Fractions were dialyzed against DMEM and filter-sterilized before use.

All experiments described below have been done at least three times with results similar or identical to those illustrated.

## RESULTS

Creatine kinase can be induced in $BC_3H1$ cells under several conditions. As shown in Fig. 1, if the cells are allowed to grow in medium containing 20% serum without medium changes (13), they cease to grow at ~ $1.8 \times 10^5$ cells/cm$^2$. After the cessation of growth, the level of creatine kinase in these cells rises. If the medium is changed daily (an experiment which can only be carried out on collagen-coated dishes to which confluent cells adhere firmly), then the cells grow to slightly higher density but the rate of induction of creatine kinase after cessation of growth is almost unaffected. Compare, in Fig. 1, the open squares (nonfed culture) with the closed squares (culture fed daily). If late in the logarithmic phase of growth the medium is changed to 0.5% serum (day 3 in the experiment in Fig. 1), cell growth ceases within 24 h, and within 48 h, one observes a rapid increase in the level of creatine kinase (closed circles in Fig. 1). Note the reproducibility of these observations in the experiments in which we compare cells on collagen-treated dishes and cells on plastic (open squares and open circles in Fig. 1).

These experiments raise the question whether the induction of creatine kinase at high cell density is due to the depletion by the cells of medium components required for growth, or is due to an event related to cell contact. If depletion of the medium is the cause of the induction of creatine kinase, it must be extremely rapid, because daily changes of medium delay but do not abolish the induction of creatine kinase. To answer this question, we have used medium obtained from confluent cells actively synthesizing creatine kinase (such as those indicated by filled squares in Fig. 1) and added this medium to sparse growing cells, to ascertain whether these sparse cells would continue to grow in this medium or whether they would cease to grow and rapidly initiate the synthesis of creatine kinase. If the former occurred, then depletion of the medium components would be considered as a likely cause of the induction of creatine kinase at high cell density, but if sparse cells continued to grow in medium conditioned by cells at high density, then depletion of medium components cannot by itself amount for the induction of creatine kinase at high density.

The data in Fig. 2 show that cells transferred to conditioned medium continue to grow for several days and do not immediately initiate the synthesis of creatine kinase; thus, medium depletion cannot account for the induction of creatine kinase at high cell density. In contrast, sparse cells at the same density, transferred to medium containing 1% serum, rapidly induce creatine kinase.

The induction of creatine kinase in sparse cells, after a change to medium containing 1% serum, is also dependent on cell density. As shown in Fig. 3, no induction is observed at very low cell density, where 1% serum will support cell growth and will not lead to the induction of creatine kinase. In contrast, daily changes of medium containing 1% serum at higher cell densities (triangles in Fig. 3) do not prevent the induction of creatine kinase. Similar observations have been made with cells plated at $2 \times 10^4$ cells/35-mm dish, corresponding to the open squares in Fig. 3, where daily feeding of the cultures does not alter the kinetics of induction of creatine kinase (see Fig. 5 below). The data suggest that cell contact is required for the cessation of growth and the induction of creatine kinase. Fig. 4 illustrates typical areas in cultures at densities in which creatine kinase can (panels *d–f*) and cannot (panels *a–c*) be induced by transfer of the culture to medium containing 1% serum. $BC_3H1$ cells tend to aggregate in patches, and even at modest cell densities the cells show extensive cell-to-cell contact and a spindly morphology under conditions where creatine kinase is induced. Panels *a, b, d,* and *e* represent cultures at the time they were transferred to 1% serum (day 2). Note that the cell densities are such that cell-cell contact is very limited in

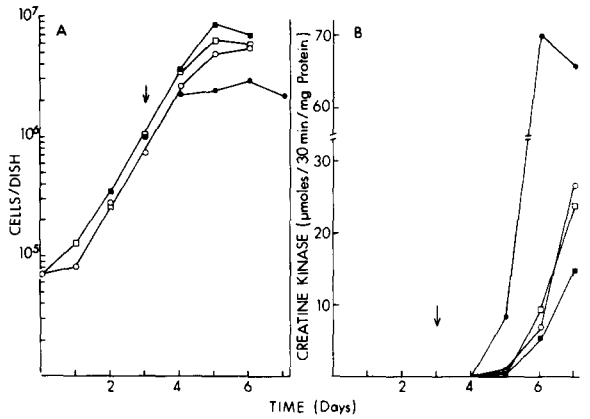


FIGURE 1 Induction of creatine kinase in $BC_3H1$ cells. Cells were plated in 60-mm Falcon dishes at a density of $7 \times 10^4$ cells/dish in DME - 20% fetal calf serum - 0.1 mg/ml glutamine, 100 U/ml penicillin and 100 μg/ml Streptomycin. Cells were plated on collagen-coated dishes (□■), or directly on plastic (○●). In the series designated (■), the medium was changed daily; in all other cultures the medium was not changed. On day 3 (designated by the arrow), one set of cultures was transferred to medium containing 0.5% fetal calf serum (●). Cell number and creatine kinase concentration were determined as described in Materials and Methods. Protein was measured colorimetrically (6). All determinations are the average of duplicate determinations.

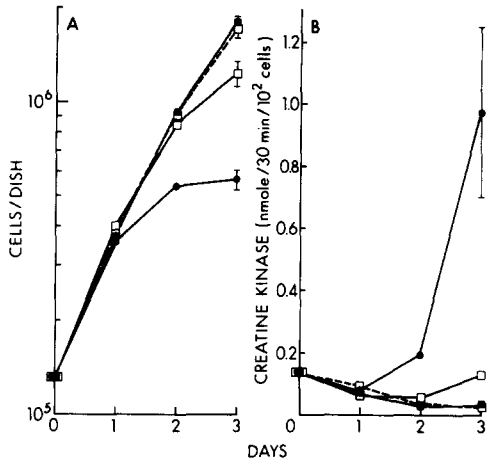


FIGURE 2 Effect of conditioned medium on growth of $BC_3H1$ cells. Cells were plated in 35-mm collagen-coated dishes in DME containing 20% fetal calf serum, glutamine, and antibiotics. On day 0, the cells were fed with fresh medium concontaining 20% fetal calf serum (■), fresh medium containing 1% fetal calf serum (●), or medium that had been incubated for 24 h either with confluent $BC_3H1$ cells (—□—) or with collagen-coated dishes lacking cells (- -□- -). Assays for cell number and creatine kinase were carried out as described in Materials and Methods. Conditioned medium was obtained from three consecutive days, corresponding to days 5, 6, and 7 of Fig. 1 (filled squares), and was frozen at the time of collection, then pooled and filtered before use. The control medium from empty dishes was prepared at the same time and handed in the same manner.

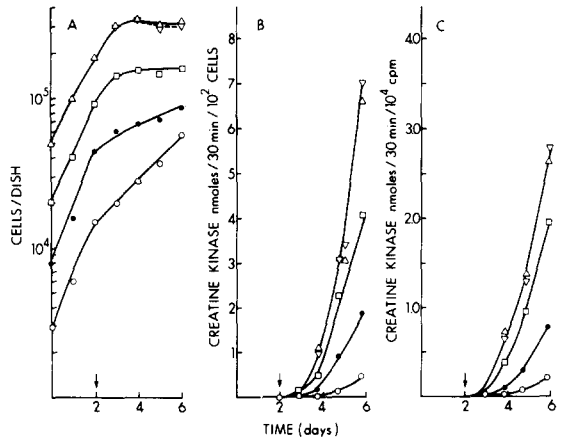


FIGURE 3 Density dependence of the induction of creatine kinase in $BC_3H1$ cells. $BC_3H1$ cells were plated in 35-mm dishes at the densities indicated in DME with antibiotics, glutamine, and 20% horse serum. At the arrow (day 2), the cells were washed and the medium was changed to medium containing 1% serum. Panel *A* documents the rate of cell growth in these cultures. Panels *B* and *C* illustrate the rate of induction of creatine kinase, normalized to cell nuer (panel *B*) and to protein (panel *C*). As described in Materials and Methods, the cultures were grown in the presence of [$^3$H]-leucine (1 $\mu$Ci/ml), and the relative protein content was determined from the amount of trichloroacetic acid-precipitable [$^3$H]leucine-labeled protein. Medium was changed every second day in all cultures, except in culture indicated by (▽) where the medium was changed daily.

the low-density cultures. Panels *c* and *f* represent the appearance of these cultures at the end of the experiment (day 6). The high-density cells show the morphology characteristic of such induced cultures, consistent with the biochemical data (open triangles, Fig. 3). The low-density cultures remain fibroblastic in appearance. Moreover, they have continued to proliferate during the 4-d period without any significant increase in creatine kinase activity or [$^{125}$I]$\alpha$-bungarotoxin binding. By day 6, they have reached a density where cell islands have formed, and they are beginning to show the biochemical differentiation (open circles, Fig. 3).

If $BC_3H1$ cells are plated at densities of $\sim 2 \times 10^4$ cells/dish and if after 2 d the medium is changed to 1% serum, induction of creatine kinase can be detected by day 4; the kinetics of induction are the same whether medium is changed daily or every second day (Fig. 5). If the medium recovered from these cultures is added to cells growing in 1% serum at lower cell density, the kinetics of growth or induction of creatine kinase are the same in conditioned medium as in fresh medium containing 1% serum. Thus, induction of creatine kinase in these cells cannot be due to depletion of a medium component, or secretion by the cells of "inducing component" which is stable in the growth medium. Cell-to-cell contact appears to be the most likely positive affect or for the induction of creatine kinase in these cultures.[1] Arrest of cell growth is not by itself sufficient to induce creatine kinase. Cells arrested with hydroxyurea do not show any induction of creatine kinase nor do they show the morphological changes associated with differentiation (data not shown). Arrest with hydroxyurea is a less than perfect control for arrest of cell growth by low serum and contact since the former occurs at the $G_1$-S interphase in the cell cycle whereas the latter are likely to affect cell growth early in $G_1$ phase of the cell cycle.

The experiments presented can be rationalized by the assumption that the induction of creatine kinase in $BC_3H1$ is determined by a balance between induction signals derived from cell-to-cell contact and repression due to one or more components present in serum.

To further test this model, we have asked whether the induction of creatine kinase once initiated can be arrested by the addition of serum. The observations in Fig. 6 show that addition of serum[2] (or serum fractions, see below) to $BC_3H1$ cells that have initiated the induction of creatine kinase will prevent further synthesis of this enzyme; compare, in Fig. 6, closed circles and dashed line (inducing conditions) with open circles and solid line (repressing conditions). The induction process thus appears to be reversible. The reversibility of the induction of a protein characteristic of differentiated cells is a unique phenomenon, and it prompted us to examine whether the synthesis of other muscle-specific proteins by $BC_3H1$ cells was subject to similar control mechanism.

Fig. 7 illustrates the induction of the acetylcholine receptor (defined by its ability to bind $^{125}$I-$\alpha$-bungarotoxin) in $BC_3H1$ cells under two sets of conditions, high cell density in 20% serum and low cell density in 1% serum. For comparison, the induction of creatine kinase has also been measured in parallel cultures. Under both conditions, synthesis of the acetylcholine receptor is induced, and in each case its appearance precedes

[1] Although we prefer to interpret the density effects on enzyme induction to reflect cell-to-cell contact, we cannot rigorously exclude that high cell density results in localized change in the cell environment which affects enzyme induction.

[2] The induction of creatine kinase can be arrested by the addition of either fetal calf serum or horse serum. All the initial experiments were carried out with fetal calf serum, but later experiments used horse serum with identical results. Both of these sera support active growth of $BC_3H1$ cells.

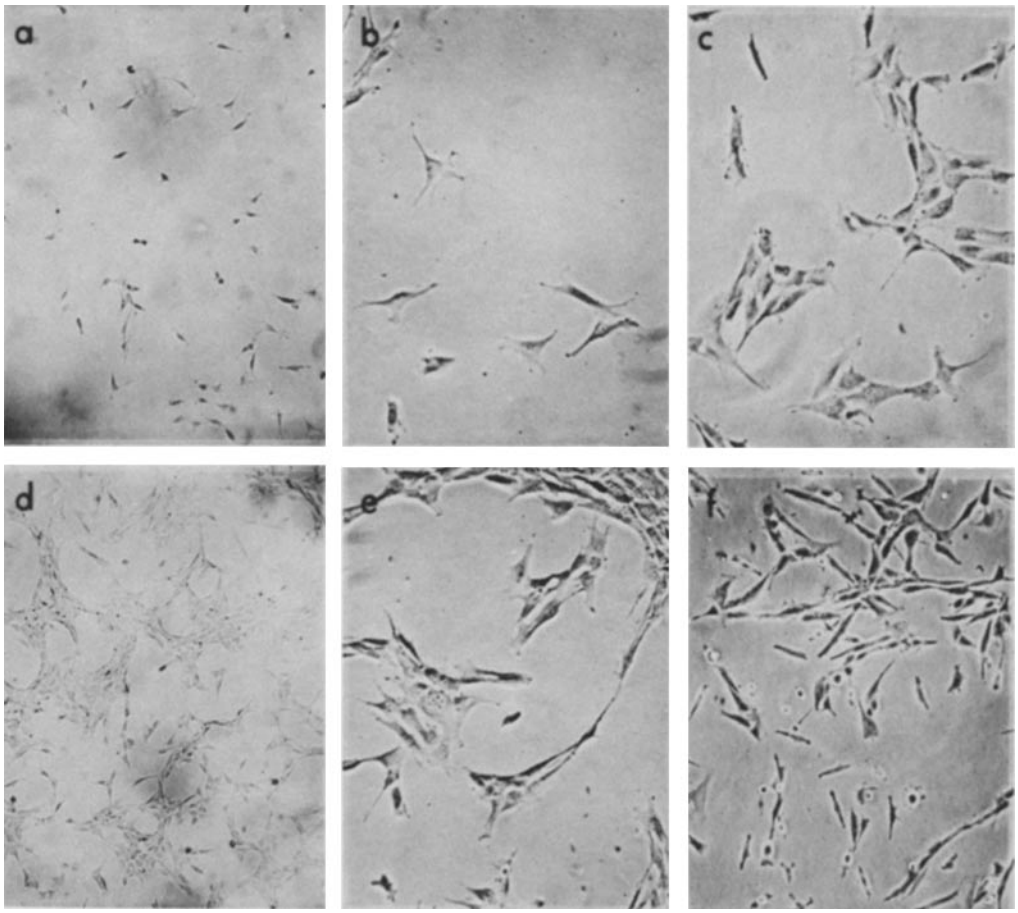


FIGURE 4 Morphology of $BC_3H1$ at different densities. The cells shown in this figure are from a parallel experiment to that shown in Fig. 3. Cells shown in panels *a–c* are plated at $3 \times 10^3$ cells/35-mm dish, corresponding to open circles in Fig. 3. Panels *a* and *b* show, at two different magnifications, cells on day 2, the day on which the medium is changed to 1% serum. Panel *c* shows the culture at the higher magnification on day 6. In Panels *d–f* the cells were plated at $5 \times 10^4$ cells/35-mm dish corresponding to the open triangles in Fig. 3, panels *d* and *e* are on day 2 and panel *f* on day 6. Note, in panel *f*, the spindly morphology characteristic of the cells that are differentiating and the fact that, even on day 2 (panel *e*), cells plated at this density are primarily present as cell clusters rather than isolated cells. In contrast, the cells shown in panels *b* and *c* remain flat, are well separated, and remain undifferentiated almost until the end of the culture period. Cultures were photographed with an inverted Nikon phase microscope. Bar, 100 μm.

by at least one day the appearance of high levels of creatine kinase activity in the same cultures. Thus, for example, when a culture that has been maintained in 20% serum for 2 d and has reached $10^5$ cells/dish in 20% serum is transferred to 1% serum, an immediate induction of the synthesis of the acetylcholine receptor is observed (open triangles in Fig. 7) where the rise in the activity of creatine kinase does not occur until day 4. Thus, if transfer to 1% serum initiates a developmental program in these cells, then the program is one in which induction of the acetylcholine receptor occurs significantly earlier than the induction of creatine kinase activity. Similar temporal differences in the induction of these two muscle-specific proteins have been observed with myoblasts (see, for example, 18).

If $BC_3H1$ cells in which a partial induction of the acetylcholine receptor has taken place in 1% serum are transferred to 20% serum, then we observe a decrease in the concentration of the acetylcholine receptor present on the surface of these cells with a half-life of ~ 40 h (Fig. 8). In control experiments using cycloheximide to inhibit protein synthesis, we observe a half-life for the acetylcholine receptor of 32 h[3] (data not shown). The decrease in the level of the acetylcholine receptor in these cells after addition of serum strongly suggests that serum prevents further synthesis (or surface expression) of this differentiated protein in partially induced cells and does not simply prevent the recruitment of new cells into the differentiation program, because if the latter were the case, the level of the surface acetylcholine receptor in the culture would either increase slowly or remain constant.

The addition of 20% serum to partially induced cells results in a slow reinitiation of growth (Fig. 6); it becomes important to consider whether the reinitiation of cell growth is required to repress the synthesis of muscle-specific proteins. We have in

[3] Previous measurement of the turnover rate of the acetylcholine receptor in $BC_3H1$ cells have been made by addition of cycloheximide to confluent cells plated in 20% serum and maintained without medium changes. Under these conditions the half-life of the acetylcholine receptor was ~ 10 h (13). It seems likely that the different culture conditions account for this difference in half-life.

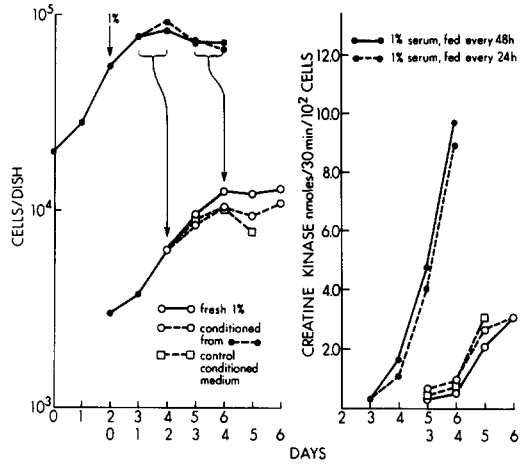


FIGURE 5 Induction of $BC_3H1$ cells in medium conditioned by sparse cells. $BC_3H1$ cells were plated in 35- dishes as described. On day 2, the medium was changed to 1% serum (●) and changed either daily (- - -) or every 2 d (——). The time scale for this culture is shown by the upper numbers on the abscissa. Medium was recovered from the cultures fed daily and used to grow a second series of cultures shown by the open symbols. Three sets of cultures were prepared and grown after day 2 (lower numbers on abscissa) either in 1% serum (○——○), or in conditioned medium as above (○- - -○) or in control conditioned medium, which had been exposed to plastic dishes with no cells for 24 h. All of these cultures show a low induction of creatine kinase characteristic of these sparse cultures, but no difference was detected between the three media.

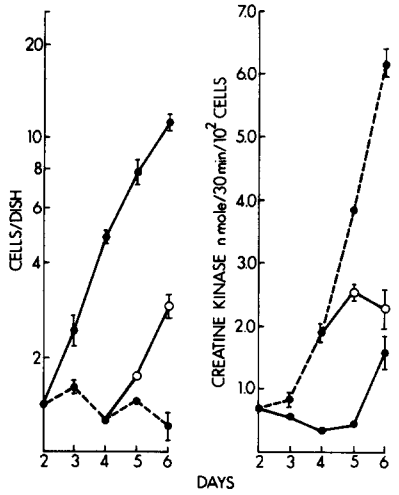


FIGURE 6 Effect of serum addition on partially induced cells. $BC_3H1$ cells were plated in 20% serum on day 1. On day 2, some dishes were transferred to medium containing 1% serum (●- - -●) while others (●——●) remained in 20% serum. On day 4, some dishes in 1% serum were transferred back to 20% serum (○——○). In this particular experiment, reinitiation of cell growth in 20% serum was extremely rapid. In cultures maintained longer in 1% serum, a variable lag period is observed before reinitiation of growth (see, for example, Fig. 10).

preliminary experiments fractionated serum as described in Materials and Methods by removal of proteins that bind to CM-Sephadex followed by gel exclusion chromatography (Fig. 9). The high molecular weight fraction from serum will repress the synthesis of creatine kinase, without reinitiating cell growth, whereas the lower molecular weight fractions have no effect (Figs. 10 and 11). Compare, in Fig. 11, panel *B*, the high

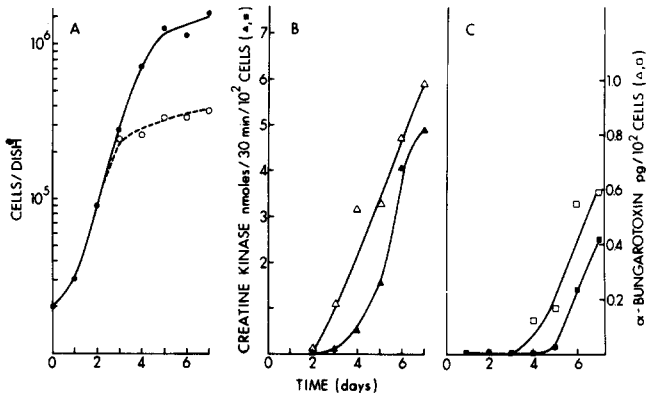


FIGURE 7 Induction of acetylcholine receptor in $BC_3H1$ cells. $BC_3H1$ cells were plated in 35-mm collagen-coated dishes in 20% serum. On day 2, some of the dishes were transferred to medium containing 1% serum. Panel *A*, cell density: (●), 20% serum, (○), 1% serum. Panel *B*, creatine kinase (▲) and specific α-bungarotoxin binding (△) to cells in 1% serum. Panel *C*, creatine kinase (■) and specific α-bungarotoxin binding (□) to cells in 20% serum. Nonspecific binding was <0.01 pg/$10^2$ cells. Note that both in 1% serum (Panel B) and at high cell density (Panel C) the induction of the acetylcholine receptor precedes the onset of creatine kinase induction by at least 1 day.

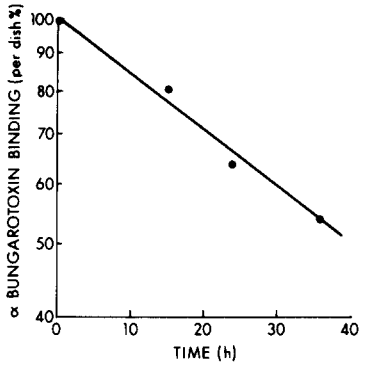


FIGURE 8 Effect of serum addition on the level of the acetylcholine receptor. $BC_3H1$ cells were plated in 20% horse serum; after 24 h the medium was changed to 1% serum. On day 4, the medium was changed to 20% serum, and at the times indicated the ability of the cells to bind [$^{125}$I]-α-bungarotoxin was determined as described in Materials and Methods. The level of specific α-bungarotoxin binding at the time of the change of the medium to 20% serum was 0.2 pg/$10^2$ cells.

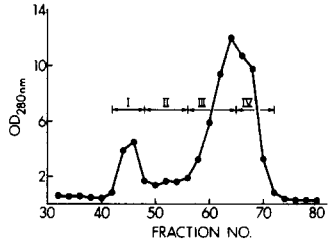


FIGURE 9 Fractionation of fetal calf serum. Fetal calf serum was fractionated as described under Materials and Methods, first by removal of proteins that are retained on CM-Sephadex, and next by gel exclusion chromatography on Sephacryl S-200. Fractions were pooled as indicated in the figure and assayed for their ability to block the induction of creatine kinase when added to cells in 1% serum at a level equivalent to that present in 20% serum. The results of these experiments are shown in Figs. 10 and 11.

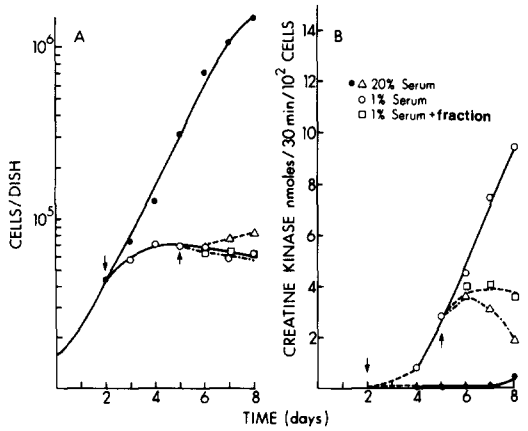


FIGURE 10 Effect of serum and serum fractions on the induction of creatine kinase. $BC_3H1$ cells were plated as described in Materials and Methods, using 10% dialyzed fetal calf serum. After 2 d the dishes were washed with DME and incubated with DME containing 15% F12 and 20% dialyzed fetal calf serum (●) or dialyzed 1% fetal calf serum (○). On day 4, cells were fed with the appropriate medium; on day 5, some of the dishes in 1% serum were transferred to medium containing 20% serum (△) or 1% serum plus Fraction I (Fig. 9) at a concentration equivalent to that present in 20% serum (□). All cultures were maintained on a 2-d feeding schedule, and creatine kinase and cell numbers were determined as described in Materials and Methods. All cultures also contained 1 μCi/ml of [$^{35}$S]-methionine. The results in panel *B* show creatine kinase normalized to cell numbers. Identical results were obtained if the creatine kinase was normalized to cell protein, measured as trichloroacetic acid-insoluble [$^{35}$S] counts.

molecular weight fraction, with panel *D*, the low molecular weight fraction. The addition of the high molecular weight fraction from serum (Fraction I, Fig. 9) does not result in reinitiation of cell growth, not only as determined by cell number (Fig. 10), but also as determined by the incorporation of [$^3$H]-thymidine into DNA, a much more sensitive measurement of the movement of cells out of the $G_1$ phase of the cell cycle and into S phase (Table I).

We conclude from these preliminary experiments that reinitiation of cell growth is not necessary for the repression of differentiation by serum components. By contrast, a variety of known mitogenic compounds including the platelet-derived growth factor, epidermal growth factor, dexamethasone and insulin do not repress differentiation. Neither fibronectin nor cold-insoluble globulin can replace the high molecular weight fraction from serum as inhibition of the induction of creatine kinase.[4]

## DISCUSSION

The observations presented are interpreted to indicate that, under our culture conditions, the induction of the creatine kinase and of the acetylcholine receptor in $BC_3H1$ cells is a reversible process. Induction of these two muscle-specific proteins is under dual control. Serum contains one or more components which inhibit differentiation whereas cell-to-cell contact[1] induces differentiation. For the purpose of this discussion, differentiation is defined as the synthesis of creatine kinase and the acetylcholine receptor. In other systems, plasma membranes added to cells have been successfully used to mimic cell contact phenomena (22); experiments are in progress to test whether membranes, when added to $BC_3H1$ cells at low density, will induce the synthesis of muscle-specific proteins.

Inhibition of differentiation can take place in the absence of cell growth (Fig. 10), and the proteins present in the high molecular weight fraction of serum are not by themselves mitogenic for $BC_3H1$ cells. Whether the functional molecules are truly high molecular weight serum proteins or whether they are bound to proteins present in the high molecular weight fraction in serum remains to be determined. The inhibition by serum or serum fractions of the induction of creatine kinase is particularly striking in light of the observations in Fig. 7. These

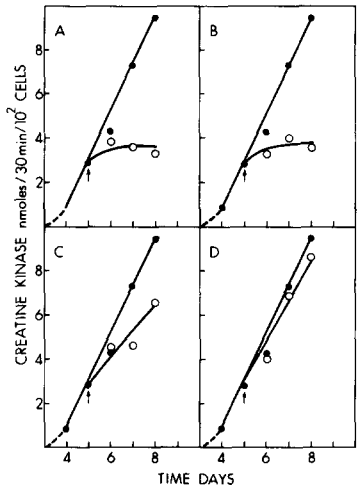


FIGURE 11 Effect of serum fractions on the induction of creatine kinase. Culture conditions used were as in Fig. 10. The cells were grown for 2 d in 10% serum, then switched to 1% serum on day 2. The creatine kinase of cultures in 1% serum is shown by (●) in each panel. In panel *A*, (○), are shown the results of adding, on day 5, the proteins not retained on CM-Sephadex to cells. In panel *B*, (○), is shown the results of adding Fraction I (Fig. 9) to the cells; in panel *C*, (○), Fraction III, and in panel *D*, Fraction IV. None of these serum fractions stimulated cell growth.

TABLE I

*DNA Synthesis in $BC_3H1$ Cells*

| Growth conditions | Rate of DNA synthesis | | |
|---|---|---|---|
| | Day 5–6 | Day 6–7 | Day 7–8 |
| | [$^3$H]/[$^{35}$S] | [$^3$H]/[$^{35}$S] | [$^3$H]/[$^{35}$S] |
| Exponentially growing cells in 20% serum | 2.7 | — | — |
| A) 1% Serum | 0.08 | 0.058 | 0.08 |
| B) Cells in *A* changed to 20% serum on day 5 | 0.13 | 0.33 | 0.46 |
| C) Cells in *A* changed to 1% serum + serum fraction I on day 5 | 0.058 | 0.069 | 0.13 |

The experiment was carried out in parallel to that shown in Fig. 10. Appropriate cultures were incubated for the 24-h periods indicated with 1 μCi/ml (0.67 mM) [$^3$H]-thymidine to determine the rate of DNA synthesis. The results are expressed as a ratio of [$^3$H]/[$^{35}$S], the latter derived from [$^{35}$S]-methionine incorporated into protein. Because the cells had been chronically labeled with [$^{35}$S]-methionine, the latter is a measure of total cell protein (22).

[4] The following compounds were tested at the concentrations indicated. Insulin (10 μg/ml), dexamethasone ($10^{-7}$ M), transferrin (5 & 25 μg/ml), fibroblast growth factor (Collaborative Research, Inc.) (20 ng/ml), human lung fibronectin (40 μg/ml), dibutyryl cAMP ($3 \times 10^{-4}$ M), and crude platelet-derived growth factor (at levels saturating for mutagenic response for 3T3 cells). These factors were tested either alone or in various combinations; none inhibited induction of muscle-specific proteins in $BC_3H1$ cells in 1% serum.

data show that the acetylcholine receptor is induced in these cells well before significant induction of creatine kinase can be detected. Thus, induction of creatine kinase activity is a relatively late event in the differentiation sequence of these cells and yet it appears to be totally reversible. The fact that the induction of the acetylcholine receptor precedes the induction of creatine kinase by one day suggests that cells that are initiating the synthesis of creatine kinase are already committed to the synthesis of at least one set of muscle-specific proteins; thus, a cell partially induced for creatine kinase is almost fully induced for the acetylcholine receptor. Similar differences in the time of appearance of muscle-specific proteins have been noted, for example, with chick myoblasts (19).

There is similarity between these observations and previous reports on the induction of S-100 protein in C-6 cells. The induction of S-100 in these cells occurs at high cell density but is also repressed by serum components that are apparently derived from platelets and which are not mitogenic for C-6 cells (8). More recently, Orly et al. (12) have demonstrated the repression by serum of differentiated function of granulosa cells.

It is not always clear to what extent observations made with established cell lines can be applied to more "normal" primary cells in culture and ultimately to cells in the whole animal. Nevertheless the observations with $BC_3H1$ cells represents an ideal model to study the role of cell-cell interactions and of serum components in controlling certain aspects of cellular differentiation. $BC_3H1$ cells are an established cell line with stable properties. Because the cells do not fuse, it has been possible to show that, at least for those cells, differentiation is not an irreversible phenomenon. Although partially differentiated cells can reinitiate growth, repression of differentiation can take place without reinitiation of cell growth. These observations are in contrast to those made by many laboratories with myoblasts, where cessation of growth is a requirement for differentiation, but where the process of differentiation, once initiated, is irreversible (see for example, reference 10).

An extensive series of investigations have been carried out with primary cultures of smooth muscle cells (for review, see Chamley-Campbell et al., reference 5). The main observation relevant to this communication is that cell division can occur at least in some differentiated smooth muscle cells, and that, in culture, growing cells will lose many characteristics of smooth muscle cells but regain these at high cell density when growth ceases (3, 4).[5]

These observations are fully compatible with the observations on $BC_3H1$ cells and suggest that $BC_3H1$ cells may be a good model for the study of the synthesis of muscle-specific protein in smooth muscle cells. One would expect, from the observations reported with $BC_3H1$ cells, that smooth muscle cells would not differentiate at low density, and would do so at confluence as a result of cell-to-cell contact. Whether serum components influence differentiation of primary smooth muscle cells is not known at the present time. $BC_3H1$ cells differ from primary cultures of smooth muscle cells in their ability to maintain the capacity to differentiate after repeated subculture and in the fact that the platelet-derived growth factor is not a mitogen for these cells. A more extensive comparison of the differentiation of $BC_3H1$ cells and smooth muscle cells in culture is clearly warranted, including the assessment of the role of serum components in the differentiation of both types of cells. Because serum lots may differ in the concentration of molecules that inhibit cell differentiation, side-by-side comparison of the effects of different serum lots on smooth muscle cells and $BC_3H1$ cells will have to be carried out.

[5] Prolonged culture of smooth muscle cells at low density results in irreversible differentiation or modulation (Chamley-Campbell et al. [5]). This may reflect the selection by prolonged growth of cells which can no longer differentiate at high cell density. That the origin of these cells in smooth muscle rather than fibroblasts can be shown in the antibodies specific for smooth muscle actin, which indicate that cells that have lost the ability to differentiate at high cell density so as to show the morphological characteristics of smooth muscle cells, still synthesize smooth muscle actin.

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