Collagen and Stretch Modulate Autocrine Secretion of Insulin-like Growth Factor-1 and Insulin-like Growth Factor Binding Proteins from Differentiated Skeletal Muscle Cells* 

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Stretch-induced skeletal muscle growth may involve increased autocrine secretion of insulin-like growth factor-1 (IGF-1) since IGF-1 is a potent growth factor for skeletal muscle hypertrophy, and stretch elevates IGF-1 mRNA levels in vivo. In tissue cultures of differentiated avian pectoralis skeletal muscle cells, nanomolar concentrations of exogenous IGF-1 stimulated growth in mechanically stretched but not static cultures. These cultures released up to 100 pg of endogenously produced IGF-1/μg of protein/day, as well as three major IGF binding proteins of 31, 36, and 43 kilodaltons (kDa). IGF-1 was secreted from both myofibers and fibroblasts coexisting in the muscle cultures. Repetitive stretch/relaxation of the differentiated skeletal muscle cells stimulated the acute release of IGF-1 during the first 4 h after initiating mechanical activity, but no increase in the long-term secretion over 24-72 h of IGF-1, or its binding proteins. Varying the intensity and frequency of stretch had no effect on the long-term efflux of IGF-1. In contrast to stretch, embedding the differentiated muscle cells in a three-dimensional collagen (Type I) matrix resulted in a 2-5-fold increase in long-term IGF-1 efflux over 24-72 h. Collagen also caused a 2-5-fold increase in the release of the IGF binding proteins. Thus, both the extracellular matrix protein type I collagen and stretch stimulate the autocrine secretion of IGF-1, but with different time kinetics. This endogenously produced growth factor may be important for the growth response of skeletal myofibers to both types of external stimuli.

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**EXPERIMENTAL PROCEDURES**

Materials—Fertilized Leghorn chicken eggs were purchased from Beaver River Farm, Kingstown, RI. Silicone rubber elastic membranes were from Dow Corning Corp., Midland, MI. Rat tail type I collagen was obtained from Collaborative Biomedical Products, Bedford, MA. Eagle's basal medium, penicillin, glutamine, and trypsin were from Life Technologies, Inc., Grand Island, NY. C18 Sep-Pak cartridges were obtained from Waters, Division of Millipore, Bedford, MA. Protein assay kits were purchased from Pierce. [125I]-insulin-like growth factor-1, donkey anti-rabbit antibody, and [1-14C]phenylalanine were from...
Amersham. Anti-IGF-1 rabbit antibody was obtained from the National Institute of Diabetes and Digestive and Kidney Diseases, National Hormone and Pituitary Program. IGF-1 standards were from Intergen Co., Purchase, NY. Polyacrylamide gel electrophoresis reagents were obtained from Bio-Rad. All other chemicals were from Sigma.

Cell Cultures—Embryonic avian skeletal muscle cells were enzymat-ically isolated from 12-day in ovo pectoralis muscle using standard dissociation techniques (25). The cells were plated on collagen-coated wells of plastic culture dishes or the elastic substratum wells of a mechanical cell stimulator (Cell Kinetics Inc., Providence, RI) at a final density of 7,950 cell/mm² as described previously (25). The cultures were maintained at 37 °C in a humidified 5% CO₂ incubator in Eagle's basal medium containing 10% horse serum, 5% chicken embryo extract, 50 units/ml penicillin, 2 mM glutamine (85/10/5). At the high plating density used in these studies myofiber formation was initiated within 36 h of plating and well formed myofibers were evident by 72 h. Some cultured cells were embedded in a three-dimensional collagen gel matrix (400 μg of collagen/well) 72 h postplating as described previously (25). To prepare cultures depleted of fibroblasts and enriched for myo-fibers, the cultures were treated with 10 μg cytosine arabinoside for 24 h at day 3 postplating. After cytosine arabinoside treatment, the cells were rinsed once, and incubated in 85/10/5 medium, or embedded in the collagen gel matrix. Fibroblast enriched cultures were obtained by plating newly isolated avian muscle cells in culture flasks for 50 min at 37 °C. The attached cells, which are mainly fibroblasts, were rinsed twice in 85/10/5 medium, and incubated in this medium for 72 h. The cells were resuspended with 0.025% trypsin for 15 min, collected by centrifugation, resuspended in 85/10/5 medium, filtered through 20–30-μm pore-size Nitex filters to remove residual myofibers, and plated in a culture flask. After reaching confluency, the cells were subcultured a second time by the same protocol, plated on collagen coated 4-well plates at a final density of 530 cells/mm², and used for the experiments when confluent. In some experiments, the confluent fibroblast cultures were also embedded in a collagen gel 72 h postplating (24).

Mechanical Stimulation—On day 6 postplating, collagen-embedded and noncollagen-embedded muscle cells were rinsed for 2 h (four 30-min rinses) in basal Eagle's medium containing 50 units/ml penicillin, and 2 mM glutamine. The rinsed cells were incubated in defined serum-free medium consisting of basal medium Eagle's, 50 units/ml penicillin, 2 mM glutamine, 0.335 mg/liter ferrous sulfate, 0.05 mg/liter sodium selenate, and 125 mg/100 ml of bovine serum albumin (muscle maintenance medium; MM medium) as described previously (25). Half of the 36 culture wells were maintained as static controls in the mechanical cell stimulator while the other 18 wells were mechanically stimulated by a pattern of activity which induces skeletal muscle hypertrophy (25) (five 12% substratum stretches and relaxations over a 20-s period followed by a 10-s rest period). This pattern was repeated twice more, followed by a 30-min rest period after the third mechanical stimulus (TRIAL39.PGM, Fig. 1). The cells were mechanically stimulated by stretching the substratum with 2-mm diameter vertically moving prongs centered on the bottom of each well. Cell stretch equals substratum stretch in this model system, as determined by morphometric measurements (25). In experiments involving changes in stretch intensity, cells were mechanically stimulated by TRIAL39.PGM but the percent stretch was varied from 6.7 to 21% by varying prong height in the elastic wells. As stretch was increased, the skeletal muscle cells were stretched and relaxed 12% by TRIAL39.PGM but with a rest period of 5 min rather than 30 min. All cells grown in plastic culture plates or in the mechanical cell stimulator were kept on a rotary shaker (40 rpm) at 37 °C when mechanically stimulated to eliminate medium stirring differences between control and stretch groups.

Extraction of Insulin-like Growth Factor-1 from Conditioned Medium—Conditioned medium was collected at various times and stored at −80 °C. Insulin-like growth factor-1 was extracted from the medium following the procedure of Brier et al. (26). Briefly, the medium was thawed, and incubated for 1 h at 21 °C with an equal volume of 0.5 M HCl to free IGF-1 from its binding proteins. The acidic medium was passed through C18 Sep-Pak columns (prewashed with isopropl alcohol, methanol, and 4% (v/v) acetic acid), and recycled once. IGF binding proteins were washed through the columns with 4% acetic acid, and IGF-1 was eluted from the columns with absolute methanol. Recovery of IGF-1 with this method was approximately 90% based on the extraction and elution of IGF-I from chicken pituitary. The IGF-I eluates were dried under nitrogen for approximately 40 min, and stored at −80 °C. Control culture medium incubated at 37 °C for an equal time period but in the absence of cells contained no measurable IGF-1 by this assay technique.

IGF-I Determination—IGF-1 was determined using a modification of the radioimmunoassay technique of Furlanetto et al. (27). Dried samples were reconstituted in RIA buffer (200 μg/ml proteinate sulfate, 30 mMol/liter Na₃HPO₄·H₂O, 0.05% (v/v) Tween 20, 0.02% (v/v) sodium azide, and 0.01 μ EDTA, pH 7.4). Sample aliquots were incubated 48 h at 4 °C with anti-rabbit IGF-1 primary antibody (1:10,000 dilution). The mixture was incubated overnight at 4 °C with approximately 20,000 cpm of [3H]-IGF-1 tracer. IGF-1 primary antibody complexes were precipitated with donkey anti-rabbit antibody for 15 min at room temperature, and collected by centrifugation at 2,000 rpm for 15 min at 4 °C. The supernatant was decanted, and the radioactivity in the pellet was measured with a Berthold Multi-Channel Counter LB2104. This method could reproducibly detect 12 to 1,000 pg of IGF-1. cDNA from chicken 12-day pectoralis muscle using standard procedures (25).

IGF-1 Neutralizing Antibody Assay—Differentially myofiber cultures were rinsed and incubated from day 5 to day 7 postplating in MM medium with either 25 or 250 μg/ml anti-IGF-1 antibody. During the last 4–6 h of incubation, protein synthesis rates were measured as outlined below.

IGF-I mRNA Determination—Total RNA was extracted using the RNAzol B method (CINNA/Biotecx, Houston, TX), and yielded 1–2 μg total RNA per 10⁵ cells, as determined spectrophotometrically. The integrity of the RNA was checked by agarose gel electrophoresis by standard techniques (28). Northern blots for IGF-1 mRNA were performed by separating 10–20 μg of total RNA on 1% agarose gels, transferring the RNA to nitrocellulose membranes, baking for 2 h at 68 °C, prehybridizing at 42 °C for 1 h (5 × Denhardt's, 5 × SSC, 50 mm sodium phosphate, pH 6.5, 0.1% SDS, 250 μg/ml salmon sperm DNA, 50% formamide), and hybridizing overnight at 42 °C in prehybridization solution containing 10³ cpm of 32P-labeled IGF-1 antisense probe. Posthybridization washes were performed according to the IGF-I cDNA probe. The membranes were exposed to Hyperfilm x-ray film (Amersham) for 24 h at −80 °C using 1 intensity screen. Ribonuclease protection assays for IGF-1 mRNA determination were also performed (28) on 20–40 μg of total RNA, using a commercially available kit (RBA-II, Ambion, Austin, TX). A pcCR2 BlueScript plasmid (gift of P. Rotwein) containing the cDNA sequence for chicken IGF-1 was used to prepare the IGF-1 mRNA probe. The plasmid was linearized at the BamHI site, and 32P-labeled antisense IGF-I probe prepared with [32P]CTP (Amersham) MaxiScript T3 transcription kit (Ambion). The probe was purified on 5% polyacrylamide, 8 × urea gels. Linearized pTRIPLEscript plasmid (Ambion) containing 1 250-base pair mouse actin gene fragment was utilized as a control for all experiments. In all experiments, Torula yeast RNA served as a negative control, while adult rat liver total RNA and chicken 12-day embryo skeletal muscle, and eye total RNA served as positive controls.

Biochemical Assays—Cells were collected, rinsed twice in phenol red-free Earle's balanced saline solution, and stored at −80 °C. Protein assays were performed on cell sonicate aliquots using the bicinchonic acid protein assay as described previously (25). Protein synthesis was determined using [3H]-[L-4C]phenylalanine incorporation into trichloro-
Acetic acid-insoluble material during a 4-6-h incubation period was also increased in mechanically-stimulated cells. In addition, myosin heavy chain protein (4), nanomolar concentrations of IGF-1 did not stimulate protein synthesis in control muscle cell cultures, but the same concentration caused a significant increase in protein/DNA ratios in mechanically-stimulated cells (Fig. 2A). The effect of IGF-1 on protein synthesis in the muscle cell cultures increased significantly by stretch (Fig. 2C). Insulin was active only at pharmacological doses in stimulating muscle cell growth since most of its growth-stimulatory effects are via the IGF-1 receptor, for which it has a low affinity (4). Similar results were obtained in three separate experiments. These data indicate that mechanical stimulation increases the sensitivity of skeletal muscle cells to exogenously added IGF-1 and insulin.

**Effect of Collagen on the Autocrine Secretion of IGF-1 from Differentiated Skeletal Muscle Cells**—One mechanism by which stretch could increase the cell's growth response to exogenously added IGF-1 would be by supplementing this with endogenously produced IGF-1. Insulin-like growth factors have been reported in conditioned medium from mammalian skeletal muscle cell lines but not primary avian muscle. Therefore, the endogenous secretion of IGF-1 from differentiated avian skeletal muscle cells was examined. The influence of embedding the muscle cells in a three-dimensional collagen gel matrix on IGF-1 efflux was measured first since the muscle cells withstand long-term repetitive stretch better when supported by an extracellular matrix (24). Collagen-embedded day 6 muscle cultures grown in plastic culture dishes were found to release 5.1 ± 0.9 pg of IGF-1/μg of protein from 0 to 24 h and 3.4 ± 0.6 pg of IGF-1/μg of protein from 24 to 48 h, which was 3-11 times greater than IGF-1 efflux from noncollagen-embedded cells (Fig. 3). The level of IGF-1 release varied significantly between different cell preparations, from 3 to 34 pg/μg of protein/24 h. The reason for this wide fluctuation in IGF-1 release from primary cell cultures is not known but it has been also found for other growth factors released from these cells (30). Each experiment was therefore repeated with at least two different cell preparations.

Within the same cell preparation, IGF-1 release was always greater when the muscle cells were grown on the elastic membranes of the mechanical cell stimulator compared to plastic

**RESULTS**

**Stretch Responses of Skeletal Muscle Cells to IGF-1 and Insulin**—The relationship between mechanical stimulation, cell growth, and IGF-1 was first examined by performing protein synthesis-IGF-1 dose-response studies on collagen-embedded static control and mechanically stimulated skeletal muscle cultures. As previously reported for control muscle cell cultures (4), nanomolar concentrations of IGF-1 did not stimulate protein synthesis or cell growth (Fig. 2A). In contrast, at concentrations which were ineffective in static cultures, IGF-1 stimulated cell growth (Fig. 2A) and protein synthesis (Fig. 2B) in mechanically-stimulated cells. In addition, myosin heavy chain content was also increased in mechanically-stimulated cells by doses of IGF-1 (12 nm) that were ineffective in control static cultures (3.5 nm versus 12 nm, Fig. 2D). Insulin, at a concentration of 5 μM, was inactive in stimulating cell growth in static cultures, but the same concentration caused a significant increase in protein/DNA ratios in mechanically-stimulated cells (Fig. 2A). The effect of IGF-1 on protein synthesis in the muscle cell cultures was also enhanced significantly by stretch (Fig. 2C). Insulin was active only at pharmacological doses in stimulating muscle cell growth since most of its growth-stimulatory effects are via the IGF-1 receptor, for which it has a low affinity (4). Similar results were obtained in three separate experiments. These data indicate that mechanical stimulation increases the sensitivity of skeletal muscle cells to exogenously added IGF-1 and insulin.
Fig. 3. Effect of collagen on IGF-1 release from skeletal muscle cells grown on plastic tissue culture dishes, or on silicone rubber membranes. On day 3 postplating, cultured muscle cells were fed either fresh 85/10/5 medium or embedded in a collagen gel matrix. On days 4 and 5, cells were rinsed and incubated in defined-serum free medium. Conditioned media were collected for the 0–24 and 24–48 h time periods, and analyzed for IGF-1. The values represent the mean ± S.E. of five to eight samples, and are compared using the unpaired t test. NCE, noncollagen embedded; CE, collagen embedded. ■, NCE, plastic; □, NCE, silicone; ■, CE, plastic; ■, CE, silicone.

culture dishes. Thus, noncollagen-embedded skeletal muscle cells grown on elastic membranes released 2.6-fold more IGF-1 after 24 h, and 7.8-fold more after 48 h, compared to cells on rigid plastic dishes (Fig. 3). When embedded in a collagen matrix, the muscle cells growing on the elastic membranes released 1.3- and 1.8-fold more IGF-1/μg of protein after 24 and 48 h of incubation in defined medium, respectively, compared to those grown on plastic culture dishes (Fig. 3). In subsequent experiments, controls were therefore always run with the same cell preparation growing on identical substrata.

To ascertain whether the increased IGF-1 found in conditioned medium from collagen-embedded cells was trapped within the collagen gels from prior incubation with serum and chicken embryo extract containing medium, collagen gels were prepared in 4-well plates with 85/10/5 medium, but without cells, and treated the same way as the muscle cell cultures. After rinsing the gels by the normal protocol, they were incubated in serum-free medium for a 24-h period, and conditioned medium collected for IGF-1 analysis. The collagen gels without cells released an average of 381 ± 42 pg of IGF-1/well/24 h, compared to 1,790 ± 270 pg of IGF-1/well/24 h observed in conditioned medium from collagen-embedded cells grown in plastic culture plates. To further examine this question, the amount of IGF-1 trapped from 85/10/5 medium in collagen gels in the presence of skeletal muscle cells was determined by preparing the collagen gels with medium containing tracer levels of 125I-IGF-1. Fresh medium containing tracer levels of 125I-IGF-1 was added to the cultures every 24 h. The 6–7-day-old cultures were then rinsed by the normal protocol, and the release of radioactivity measured over a 24-h period. The rinsed muscle cells embedded in the collagen matrix released 6.88% of the total initial medium radioactivity over a 24-h period. This equaled 42 pg of IGF-1/μg of protein/24 h, compared to 10–15-fold less than the IGF-1 released from collagen-embedded cells into the medium during this time period. The 125I-IGF-1 measured in homogenates of the collagen-embedded cells from these experiments was 1.9% of the total radioactivity in the original 85/10/5 medium. These results indicate that only a small percent of the IGF-1 released into the conditioned medium resulted from IGF-1 trapped from serum and embryo extract containing medium.

Effect of Mechanical Stimulation on IGF-1 Release from Cultured Skeletal Muscle Cells—To assess the effect of stretch on IGF-1 release, 6-day-old collagen-embedded cultures of differentiated skeletal muscle cells grown on silicone rubber membranes were mechanically stimulated 12% every 30 min from day 6 to day 9 postplating as outlined under "Experimental Procedures." The efflux of IGF-1 into the medium over a 12–24 h period was approximately 20–80 pg/μg of protein, and there was no significant difference between control and stretched cultures (Fig. 4). No responses to mechanical stimulation were observed when muscle cells were stretched for up to days 10 and 11 postplating (data not shown).

The effect of different patterns of mechanical stimulation on IGF-1 efflux from the collagen-embedded muscle cells was examined next. The cells were mechanically stimulated 6.7–21% every 30 min for 24 h with the same frequency as in TRIAL39.PGM. No significant differences in IGF-1 efflux were observed among the different stretch intensity groups (Fig. 5A). Similarly, a 6-fold increase in the frequency of mechanical stimulation (5-min rest periods, TRIAL52.PGM) showed no effect on the release of IGF-1 from the muscle cells (Fig. 5B).

To examine the time course of IGF-1 efflux with stretch, day 6 noncollagen-embedded cells were mechanically stimulated using the TRIAL39.PGM activity pattern, and conditioned medium was collected at 1, 2, 4, 5, 12, and 24 h of stretch, with fresh medium added to the cultures at each time point. Noncollagen-embedded cultures were used in these kinetic studies to eliminate the collagen as a potential diffusion barrier. While total accumulated release of IGF-1 over the 24-h incubation period (i.e. addition of released IGF-1 at all the time points) was not significantly different in these noncollagen-embedded cultures (control static cultures: 18.7 pg of IGF-1/μg of protein/24 h; stretched cultures: 18.4 pg of IGF-1/μg of protein/24 h), as found for the collagen-embedded culture experiments described above, the kinetics of IGF-1 release was significantly different between control and stretched cells. IGF-1 release from static control cells increased rapidly during the first 4 h and then increased at a slower rate over the remaining 20-h period (Fig. 6). IGF-1 release from stretched cells was signifi-
Fig. 5. Effect of stretch intensity and frequency on IGF-1 efflux. Collagen-embedded skeletal muscle cells were switched to defined MM medium from day 6 to day 8 postplating. Cultures in A were mechanically stimulated for 24 h by the same frequency pattern as outlined in Fig. 1, but with varied percent intensities of stretch. This experiment was performed with the same cell preparation by varying prong heights between wells as described under "Experimental Procedures." Cultures in B were mechanically stimulated every 5 min instead of every 30 min by the same pattern of activity as outlined in Fig. 1. Results are expressed as the mean ± S.E. of six values per group and compared by t test for unpaired values.

Fig. 6. Time course of IGF-1 efflux from noncollagen-embedded skeletal muscle cells. The cells were mechanically stimulated by TRAIL39.PGM. The media was removed at each time point, and fresh defined MM media added. IGF-1 content was assayed in each sample as outlined under "Experimental Procedures." Results are expressed as the mean ± S.E. of 2–3 values and compared by t test for unpaired values.

IGF-1 mRNA.

Comparison of IGF-1 Secretion from Myofibers and Fibroblasts—Because avian skeletal muscle cultures contain both myofibers and fibroblasts, we determined which cell type contributes to the IGF-1 released into the medium, and which cell type was stimulated to release IGF-1 when collagen-embedded. Noncollagen and collagen-embedded mixed cultures containing both cell types, myofiber-enriched cultures, and fibroblast-enriched cultures were prepared as outlined under "Experimental Procedures." At day 6 postplating the cells were rinsed, and incubated for 24–48 h in defined serum-free medium. Both myofiber-enriched cultures and confluent fibroblast cultures released IGF-1 under both noncollagen- and collagen-embedded conditions (Fig. 7). Noncollagen-embedded cells released lower amounts of IGF-1 than collagen-embedded cells in both cell types (Fig. 7, A versus B). On a per unit of microgram of cellular protein basis, collagen-embedded fibroblast cultures produced 1.7–2.4 times more IGF-1 than collagen-embedded myofibers at 24 and 48 h of incubation in defined medium. Interestingly, on a per unit protein basis, mixed cultures effluxed less IGF-1 than either of the two cell types alone.

Autocrine/Paracrine Effect of IGF-1 Released from Differentiated Skeletal Muscle Cells—Insulin-like growth factors can modulate anabolic processes in a number of cells including those from which they originate (12). Therefore we examined the effect of locally released IGF-1 on the differentiated skeletal muscle cells. Noncollagen-embedded and collagen-embedded skeletal muscle cells were preincubated in serum-free medium in the presence or absence of anti-IGF-1 antibody for 48 h, and L-[U-14C]phenylalanine incorporation into cellular proteins followed over a 4-h incubation period. Compared to control cells, protein synthesis was decreased 52 and 29% in the antibody-treated noncollagen-embedded and collagen-embedded cells, respectively (Fig. 8).

IGF Binding Protein Secretion from Cultured Skeletal Muscle Cells—The physiological responses of insulin-like growth factors are modulated by IGF binding proteins, and their secretion might be altered by collagen embedding or mechanical stimulation. The release of IGF binding proteins from the differentiated avian skeletal muscle cultures was therefore examined. Gel electrophoresis and ligand blotting of conditioned medium from the skeletal muscle cultures revealed the presence of three IGF binding proteins of molecular masses 31, 36, and 43 kilodaltons (kDa) (Fig. 9). The 36-kDa band was the predominant secreted binding protein from the avian cells. The effects of collagen and stretch on the efflux of these binding proteins was studied over a 24-h period. Compared to noncollagen-embedded static muscle cells, cells embedded in a colla-

2 P. Rotwein, personal communication.
Autocrine Secretion of Insulin-like Growth Factor-1

Fig. 7. Collagen-induced efflux of IGF-1 from skeletal muscle mixed cultures, skeletal myofiber-enriched, and fibroblast-enriched cultures. Myofiber-enriched cultures and fibroblast only cultures were prepared as described under "Experimental Procedures." Six-day-old cultures were incubated in defined MM medium for 24-48 h and IGF-1 efflux measured from noncollagen-embedded (A) and collagen-embedded (B) cells. Results are expressed as the mean ± S.E. of four values and compared by unpaired t test. ■, mixed cultures; □, myofiber-enriched cultures; ■, fibroblast-enriched cultures.

FIG. 8. Effect of anti-IGF-1 antibody on protein synthesis in noncollagen-embedded and collagen-embedded skeletal muscle cells. Five-day-old noncollagen-embedded and collagen-embedded skeletal muscle cells were rinsed and preincubated for 48 h in MM medium containing 25 and 250 μg of anti-IGF-1 rabbit antibody, respectively. Control cells were preincubated in MM medium without the antibody for 48 h. Protein synthesis was assayed over a 4-6-h time period, with or without the antibody. Values are expressed as the mean ± S.E. of 8 values and compared by unpaired t test.

FIG. 9. Detection of IGF binding proteins released from skeletal muscle cell cultures. Conditioned medium was analyzed for IGF binding proteins using ligand blots as described under "Experimental Procedures." The autoradiography shows three binding proteins of molecular masses 31, 36, and 43 kDa. No significant differences in IGF binding protein levels were detected between control (C) and stretched (S) cultures.

This is the first report assessing the efflux of IGF-1 from differentiated primary avian skeletal muscle cells in tissue culture. This study revealed that primary cultures of well-differentiated skeletal myofibers release IGF-1 in significant amounts. Autocrine secretion of IGF-1 has been hypothesized to be involved in work-induced skeletal muscle growth in vivo (16), and we tested this hypothesis with an in vitro model of stretch-induced skeletal muscle growth. Mechanical stretch influenced the sensitivity of skeletal muscle cells to exogenously added IGF-1, and increased the acute but not long-term release of IGF-1 from these cells. On a nanomolar basis, the acute release of IGF-1 with stretch was found to be 20-40-fold less than the amount of recombinant IGF-1 required to stimulate muscle growth in mechanically stimulated cultures.
release of the intracellular IGF-I, as part of a repair process.

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synthesized IGF-1. Immunocytochemical studies demonstrate
in vitro.

in vitro. If the stretch-induced autocrine production of IGF-1 is
involved in stretch-induced muscle growth, it must be either
more biologically active or more accessible to the IGF-1 recep-
tor than exogenously added recombinant human IGF-1.

The acute secretion of IGF-1 from cultured skeletal muscle
cells in response to mechanical stimulation is very similar to
the acute, but not long-term, stretch-induced release of atrial
natriuretic peptide from cardiac cells (34). It may result from
the release of already synthesized IGF-1, rather than newly
synthesized IGF-1. Immunocytochemical studies demonstrate
that the cytoplasm of myoblasts and newly formed myotubes
contains increased IGF-1 levels during muscle regeneration in vivo (13, 14, 35). In the present study, skeletal muscle cells
were utilized 3 or 4 days after myofiber formation in vitro, and
it is possible that these cells also contain intracellular IGF-1
stores. During the first hour of mechanical stimulation in vitro,
differentiated skeletal muscle cells appear to be partially dam-
aged, based on temporary creatine kinase release and protease
activation in the stretched skeletal muscle cells (25). The par-
tial damage to the muscle cells by stretch could result in the
release of the intracellular IGF-1, as part of a repair process.

Differentiated avian pectoralis muscle cells were found to
secrete not only IGF-1 but also IGF binding proteins of molecu-
lar masses 31, 36, and 43 kDa. This is the first report on the
secretion of IGF binding proteins from differentiated avian
skeletal muscle cells. A number of studies have shown the
presence of IGF binding proteins in human and chicken serum
(18, 33), and human amniotic fluid (21), as well as in condi-
tioned medium of tissue cultured liver cells (18), and mamma-
lian muscle cell lines (1, 22). The C2C12 cell line secretes a
single IGF binding protein of 29 kDa (22), while the C2C12 cell
line releases three binding proteins of molecular masses 24, 30,
and 32 kDa (1). The three IGF binding proteins released from
the primary avian skeletal muscle cells are similar in molecular
mass to the binding proteins found in avian serum in vivo
(28, 33, and 41 kDa) (33). Mechanical stimulation of the skel-
etal muscle cells had no significant effect on the efflux rate of
IGF binding proteins at any of the time periods studied.

A second significant finding in this study was the increased
release of IGF-1 and IGF binding proteins from skeletal muscle
cells after embedding them in a three-dimensional type I colla-
gen matrix. Collagen-embedded cells released 3–11 times
more IGF-1 than noncollagen-embedded cells. There is evi-
dence that IGF-1 stimulates collagen synthesis (36) but there
appear to be no studies on the effect of collagen on IGF-1
release. Embedding the myofibers in a collagen gel matrix
stimulates their hypertrophy (24, 37), possibly by activating
IGF-1 synthesis and secretion as a paracrine/autocrine growth
factor. The mechanism by which collagen enhances IGF-1 re-
lease from avian pectoralis muscle cells is not known. In dif-
ferentiating hepatocytes, collagen promotes the activity of
transcription factors resulting in the increased transcription of
serum protein genes, such as albumin (38, 39). Collagen may
interact with cell surface receptors resulting in increased tran-
scription of the IGF-1 gene. Because collagen type I recognizes
and binds to integrins (40–42), the effects of collagen on IGF-1
expression may be modulated via these receptors.

In addition to the differences in IGF-1 efflux from noncolla-
gen-embedded and collagen-embedded cells, skeletal muscle
cells grown on a silicone rubber substratum consistently re-
leased greater amounts of IGF-1 into the conditioned medium
than when grown on plastic culture plates. These results indi-
cate the importance of running proper controls of cells growing
on identical substratum. The elastic substratum may have
greater permeability than polystyrene plastic to gases such as
oxygen and carbon dioxide, resulting in increased cellular ac-
tivities and leading to elevated levels of IGF-1 production.
Skeletal muscle hypoxia not only reduces muscle mass but also
reduces oxidative metabolism in the muscle tissue (43).

The tissue cultures utilized in these experiments consisted of
two main cell types, myofibers and fibroblasts. Lowe et al. (44)
reported that fibroblasts are capable of synthesizing IGF-1 in vivo.
Our experiments using enriched myofiber or confluent
fibroblast cultures showed that both cell types are capable of
releasing IGF-1. Whereas in mouse primary skeletal muscle
cultures the muscle cells produce greater amounts of IGF-1
than fibroblasts (11), the avian fibroblasts released greater
amounts of IGF-1 than the enriched myofiber cultures on a
microgram cellular protein basis. But, since 80–90% of the
cellular protein in the mixed avian muscle cultures utilized in
this study arises from skeletal myofibers (30), the production of
IGF-1 by the myofibers in these cultures on a microgram cell
protein basis constitutes the major part of total IGF-1 release.
It is difficult, however, to determine the exact contribution of
each cell type in the mixed cultures since the two cell types
appear to interact in regulating total IGF-1 efflux in a complex
manner when co-cultured (Fig. 7), as found previously for the
regulation of total protein degradation in the two cell types
(45). IGF-1 secretion in mixed cultures was less than in either
cell type alone, indicating some form of feedback inhibition
when the two cell types are cultured together.

IGF-1 secreted from cultured skeletal muscle cells can be considered an important autocrine factor. Our experiments showed that protein synthesis rates are significantly reduced in the muscle cells when incubated in the presence of anti-IGF-1 antibody. Similarly, \(^{3}H\)thymidine uptake in fetal rat myoblasts was blocked when these cells were incubated with a monoclonal antibody against human somatomedin (12). Locally produced IGF-1 therefore plays an important role in the maintenance of tissue-cultured skeletal muscle cells due to its effects on anabolic processes.

In summary, this paper shows that IGF-1 and IGF binding proteins are released from differentiated avian pectoralis muscle cell cultures, and that the long-term in vitro release of these proteins from the muscle cells is not significantly stimulated by stretch. Stretch-induced myofiber hypertrophy in cultured skeletal muscle cells may involve the short-term increase in IGF-1 secretion, changes in IGF-1 receptors, or a non-IGF-1-related mechanism. In addition, significant collagen-induced IGF-1 and IGF binding protein release from the differentiated muscle cells occurs in vitro. Further studies are needed to examine the mechanisms leading to collagen-induced IGF-1 and IGF binding protein synthesis and/or release from skeletal muscle cells.

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REFERENCES