Integrin α Subunit Ratios, Cytoplasmic Domains, and Growth Factor Synergy Regulate Muscle Proliferation and Differentiation

Sarita K. Sastry, Margot Lakonishok,* Dori A. Thomas,* John Muschler, and Alan F. Horwitz*
Departments of Biochemistry and *Cell and Structural Biology, University of Illinois, Urbana, Illinois 61801

Abstract. The role of integrins in muscle differentiation was addressed by ectopic expression of integrin α subunits in primary quail skeletal muscle, a culture system particularly amenable to efficient transfection and expression of exogenous genes. Ectopic expression of either the human α5 subunit or the chicken α6 subunit produced contrasting phenotypes. The α5-transfected myoblasts remain in the proliferative phase and are differentiation inhibited even in confluent cultures. In contrast, myoblasts that overexpress the α6 subunit exhibit inhibited proliferation and substantial differentiation. Antisense suppression of endogenous quail α6 expression inhibits myoblast differentiation resulting in sustained proliferation. These effects of ectopic α subunit expression are mediated, to a large extent, by the cytoplasmic domains. Ectopic expression of chimeric α subunits, α5ex/6cyto and α6ex/5cyto, produced phenotypes opposite to those observed with ectopic α5 or α6 expression. Myoblasts that express α5ex/6cyto show decreased proliferation while differentiation is partially restored. In contrast, the α6ex/5cyto transfectants remain in the proliferative phase unless allowed to become confluent for at least 24 h. Furthermore, expression of human α5 subunit cytoplasmic domain truncations, before and after the conserved GFFKR motif, shows that this sequence is important in α5 regulation of differentiation. Ectopic α5 and α6 expression also results in contrasting responses to the mitogenic effects of serum growth factors. Myoblasts expressing the human α5 subunit differentiate only in the absence of serum while differentiation of untransfected and α6-transfected myoblasts is insensitive to serum concentration. Addition of individual, exogenous growth factors to α5-transfected myoblasts results in unique responses that differ from their effects on untransfected cells. Both bFGF or TGFβ inhibit the serum-free differentiation of α5-transfected myoblasts, but differ in that bFGF stimulates proliferation whereas TGF-β inhibits it. Insulin or TGF-α promote proliferation and differentiation of α5-transfected myoblasts; however, insulin alters myotube morphology. TGF-α or PDGF-BB enhance muscle α-actinin organization into myofibrils, which is impaired in differentiated α5 cultures. With the exception of TGF-α, these growth factor effects are not apparent in untransfected myoblasts. Finally, myoblast survival under serum-free conditions is enhanced by ectopic α5 expression only in the presence of bFGF and insulin while TGF-α and TGF-β promote survival of untransfected myoblasts. Our observations demonstrate (1) a specificity for integrin α subunits in regulating myoblast proliferation and differentiation; (2) that the ratio of integrin expression can affect the decision to proliferate or differentiate; (3) a role for the α subunit cytoplasmic domain in mediating proliferative and differentiative signals; and (4) the regulation of proliferation, differentiation, cytoskeletal assembly, and cell survival depend critically on the expression levels of different integrins and the growth factor environment in which the cells reside.

A role for the extracellular matrix (ECM)1 in the regulation of cell differentiation and gene expression has been demonstrated for many different cell types (Adams and Watt, 1993; Damsky and Werb, 1992; Juliano and Haskill, 1993; Lin and Bissell, 1993). For instance, tissue-specific expression of milk proteins in mammary epithelium requires adhesion to basement membrane components (Roskelley et al., 1995) and terminal differentiation of keratinocytes involves changes in adhesion to fibronectin (FN), laminin (LM), and collagen (Adams and Watt, 1990). However, the mechanisms by which the ECM regulates differentiation are currently poorly understood. Skeletal muscle has served as a model system for defining the molecules and mechanisms which govern cell differentiation, including its regulation by the ECM. A requirement for particular ECM components in skeletal

1. Abbreviations used in this paper: BrdU, 5-bromo-2'-deoxyuridine; ECM, extracellular matrix; FACS, fluorescence-activated cell sorting; FN, fibronectin; LM, laminin; UT, untransfected myoblast.
muscle differentiation in vitro is among the early descriptions of the requirement of a matrix molecule for differentiation (Hauschka and Konigsberg, 1966). Adhesion of muscle cells to extracellular matrix components influences such diverse phenomena as cell migration, the proliferative to differentiative transition, muscle morphogenesis, the organization of an elaborate contractile apparatus, and synapse formation (McDonald et al., 1995a). It is also apparent that other types of exogenous molecules, e.g., growth factors, regulate muscle differentiation. For example, media rich in growth factors or the presence of bFGF inhibit terminal differentiation and stimulate myoblast proliferation (Clegg et al., 1987). Conversely, the presence of insulin appears to promote differentiation (Fiorini and Magri, 1989).

Integrins, which are dual receptors for the ECM and the cytoskeleton, are implicated as key players in many aspects of muscle differentiation and development (McDonald et al., 1995a); however, the role of specific integrins is only beginning to be addressed. Menko and Boettiger (1987) demonstrated that antibody ligation of the B1 integrin maintains chick myoblasts in the proliferative state. Thus, B1 integrins participate in the transition from proliferation to differentiation. Several recent studies describe the expression and potential functions of a number of different integrins during myogenesis. The α5β1 integrin localizes in adhesion plaques and displays a dynamic and regulated pattern of expression during terminal differentiation suggesting an important role in the early events of myogenesis (Blaschuk and Holland, 1994; Boettiger et al., 1995; Enomoto et al., 1993; Lakonishok et al., 1992). The α4β1 integrin is proposed to function in fusion events during secondary myogenesis (Rosen et al., 1992). The α7β1 integrin localizes in myotendinous junctions (MTJ) (Bao et al., 1993) and several alternately spliced isoforms have been identified which are expressed in skeletal muscle (Collo et al., 1993; Song et al., 1992, 1993; Ziober et al., 1993). The α3 and αv integrins colocalize with nascent myofibrils and with z-bands, respectively, and are thus likely to take part in myofibril organization (McDonald et al., 1995b). The α1β1 (Duband et al., 1992), α6β1 (Bronner-Fraser et al., 1992), and α9β1 (Palmer et al., 1993) integrins are also expressed in skeletal muscle; however, their functions have not been identified. Although the precise role of these α subunits in muscle differentiation remains unclear, the existing data argue for distinct roles for specific integrins during myogenesis.

We addressed the role of integrins in muscle differentiation by ectopic expression of integrin α subunits in primary quail skeletal muscle cultures. Primary quail myoblasts offer many advantages for the ectopic expression of integrins. They provide a relatively continuous source of replicating myoblasts that are amenable to selection and cloning and can be stably transfected with high efficiency (DiMario et al., 1993). Furthermore, unlike many muscle cell lines which often exhibit abnormal or aborted development (Antin and Ordahl, 1991), myogenic differentiation is more faithfully reproduced in primary muscle cultures. In addition, cloned quail myoblasts, introduced into chick embryos, incorporate into developing embryonic muscle and are thus useful for in vivo studies (Stockdale et al., 1990). Two α subunits were chosen for these studies: the α5 subunit and the α6 subunit. Previous studies suggest that FN and LM play opposing roles in muscle differentiation (von der Mark and Ocalan, 1989; Kosher and Rodgers, 1987; Foster et al., 1987). The α5β1 and α6β1 integrins are specific receptors for FN and LM, respectively, making them attractive candidates to mediate these different signals. Furthermore, the α5 integrin is implicated in transmembrane signaling and gene regulation (Damsky and Werb, 1992; Juliano and Haskill, 1993) and displays a dynamic pattern of expression during muscle differentiation (Blaschuk and Holland, 1994; Enomoto et al., 1993; Lakonishok et al., 1992). The α6 integrin is also implicated in transmembrane signaling (Jewell et al., 1995; Shaw et al., 1993, 1995), and its adhesive function often depends on cell activation by phorbol esters (Delwel et al., 1993; Shaw et al., 1990). In addition, the α6 subunit is expressed throughout myogenesis (Bronner-Fraser et al., 1992; McDonald et al., 1995a), suggesting that it plays an important role.

With this system we show that changes in integrin expression have dramatic effects on myoblast proliferation and differentiation. We first demonstrate a specificity for α subunit function during differentiation. Ectopic expression of the α5 subunit inhibits differentiation and maintains myoblasts in the proliferative phase while ectopic α6 expression inhibits proliferation but not differentiation. Antisense suppression of endogenous quail α6 expression also inhibits differentiation resulting in sustained proliferation, suggesting that the ratios of integrin expression are important in the decision to proliferate or differentiate. We also show that the effect of ectopic α5 or α6 expression on proliferation and differentiation is mediated by the α subunit cytoplasmic domain. Finally, we demonstrate that integrin regulation of myoblast proliferation and differentiation depends on the growth factor environment in which the cells reside. The precise phenotype depends on the specific integrin expressed and on the particular growth factor present. Taken together, our results point to an integrated, combinatorial model of signaling events that include growth factors and integrins as regulators of differentiation.

Materials and Methods

Primary Cell Culture

Primary myoblasts were isolated from pectoralis muscle of nine day Japanese quail embryos as described (Konigsberg, 1979). Briefly, myoblasts were dissociated from muscle tissue with 0.1% dispase (Boehringer-Mannheim Corp., Indianapolis, IN) in PBS. The cell suspension was filtered through a Sweeney filter; cells were seeded onto gelatin-coated tissue culture plates (0.1% gelatin in PBS). Myoblast cultures were maintained in complete myoblast medium (DMEM [Sigma Chem. Co., St. Louis, MO] containing 15% horse serum, 5% chick embryo extract, 1% pen/strep, and 1.25 μg/ml fungizone [GIBCO BRL, Gaithersburg, MD]). Myoblasts were subcultured in trypsin-EDTA (0.06% trypsin, 0.02% EDTA) and used between passages 1 and 10.

Antibodies and Extracellular Matrix Ligands

The muscle α-actinin specific monoclonal antibody (mAb), 9A2B8, was kindly provided by D. Fishman (Cornell University, New York, NY) as a hybridoma supernatant. The mAb, VIF4, which recognizes the human α5 integrin extracellular domain was a gift of R. Isberg (Tufts University, Boston, MA). The chicken α6 specific polyclonal antibody, 9E9 (de Cur-
Vector Construction and Site-directed Mutagenesis

The human α5 cDNA ([Argraves et al., 1987]) was kindly provided by Dr. L. Reichardt in the eukaryotic expression plasmid, pBAP1-neo (Gunn et al., 1987) and subcloned into the eukaryotic expression vector, pR8Vneo (Rezza et al., 1992), or into the retroviral plasmid 1654 (a gift of Dr. M. Holm-Swarm sarcoma as described (Kleinman et al., 1982). Laminin was isolated from murine Englebreth-Holm-Swarm sarcoma as described (Kleinman et al., 1982).

The human α5 cDNA (Argraves et al., 1987) was kindly provided by Dr. R. Blackman (University of Illinois) and was cloned into pRSVneo using KpnI. The mutant α5 cytoplasmic domains were subcloned into pUC19 (USB) with BclI and by single-stranded DNA sequencing using the dideoxynucleotide chain termination method according to the Sequenase protocol (United States Biochemical Corp., Cleveland, OH) at HindIII and SmaI sites in the polylinker. A 1.2-kb HindIII-Sall fragment was then subcloned into pRSVneo at Sall on both sides to amplify pRSVneo at Sall site to amplify α5-Sall. The 4.2-kb α5 cDNA was then subcloned into pRSVneo at Sall in the sense orientation and into 1654 at XbaI in both the sense and antisense orientations. Proper insert orientation was determined by restriction endonuclease digestion. The chicken α5 cDNA (de Curtis et al., 1991) was also provided by Dr. L. Reichardt in two fragments, C1 and C5, at 5′ phase. The C1 and C5 fragments were excised with EcoRI and each cloned into pTZ18R at the EcoRI site in the polylinker. The C1 and C5 fragments were partially digested with EcoRI and completely digested with Sall, ligated to each other at EcoRI to produce a 3.4-kb full-length α5-Sall fragment and cloned into pRSVneo at Sall. The chicken α5 antisense (α5b) plasmid was constructed by excising the full-length α5-Sall cDNA with Kpnl, religating to pRSVneo, and screening for inverted orientation by restriction endonuclease digestion. The human α6 cDNA, in the expression plasmid pRc/CMV (Shaw et al., 1993), was a generous gift of Dr. A. Mercurio. The lacZ cDNA was a gift of Dr. R. Blackman (University of Illinois) and was cloned into pRSVneo at Kpnl and Sall.

Transduction mutants of the α6 cytoplasmic domain were generated as described (Hayaishi et al., 1990) using the Muta-Gene™ in vitro mutagenesis kit (BioRad Labs., Hercules, CA). Oligonucleotides were synthesized at the University of Illinois Genetic Engineering Facility (Urbana, IL). For the α5-GFFKR deletion mutant, a 1.2-kb HindIII-DraI fragment, corresponding to the α5 cytoplasmic domain, was cloned into M13mp18 using HindIII and Sall. To make the α5-GFFKR deletion, a 2.5-kb XhoI-DraI fragment was inserted into pRSVneo at Sall and Sall, ligated to each other at EcoRI to produce a 3.4-kb full-length α5-Sall fragment and cloned into pRSVneo at Sall. The chicken α6 cDNA (Argraves et al., 1987) was kindly provided by Dr. R. Blackman (University of Illinois) and was cloned into pRSVneo using KpnI and Sall.

The α5α6α5GFFKR chimeric α subunit was created by cassetting mutagenesis using complementary oligonucleotides encoding the entire human α6A cytoplasmic domain (Tamura et al., 1990) with HindIII sites engineered at both ends. This cassette was cloned into the α5 cDNA (pBAP1-neo) at the unique HindIII site which corresponds to the KL sequence of the α5 cytoplasmic domain immediately upstream of the conserved GFFKR region. Correct insert orientation was confirmed by DNA sequencing. The sequence was then confirmed by DNA sequencing. DNA cloning and sequencing were performed in the University of Illinois Genetic Engineering Facility (Urbana, IL) using the Sequenase protocol (United States Biochemical Corp., Cleveland, OH) at HindIII and Kpnl, and then into the full-length α5 cDNA in pBAP1-neo using complete HindIII-partial NdeI digests. The integrity of subcloning into the β-actin expression vector was verified by DNA sequencing. Full-length mutant α5 cDNAs were subcloned into pRSVneo using Kpnl.

Chimeric α Subunit Construction

The α5α6α5α5GFFKR chimeric α subunit was created by cassetting mutagenesis using complementary oligonucleotides encoding the entire human α6A cytoplasmic domain (Tamura et al., 1990) with HindIII sites engineered at both ends. This cassette was cloned into the α5 cDNA (in pBAP1-neo) at the unique HindIII site which corresponds to the KL sequence of the α5 cytoplasmic domain immediately upstream of the conserved GFFKR region. Correct insert orientation was confirmed by DNA sequencing. To match the α5 cytoplasmic domain sequence exactly to the published sequence (Ruoslahti et al., 1982), the KCGFFKR sequence was changed to KCGFFKR using the Mutagen kit. To clone the α5α6α5α5GFFKR hybrid cDNA into pRSVneo, a 1.5-kb Xhol-NdeI fragment was inserted into pUC19 which was subcloned into pRSVneo at XhoI and NdeI sites in the α5 cDNA. The full-length α5α6α5α5GFFKR cDNA was cloned into pRSVneo using Kpnl.

Proliferation, Differentiation, and Cell Survival Measurements

Untransfected or transfected myoblasts were trypsinized, washed twice with Puck’s Saline G (GIBCO-BRL), and seeded onto fibronectin-α5-transfected cells (20 μg/ml) or laminin-α6-transfected cells (40 μg/ml) coated 12-mm glass coverslip using a density of 1.6 × 10^9 cells/cm^2 in complete myoblast medium or 3.2 × 10^6 cells/cm^2 in selection medium (DMEM + 2% bovine serum albumin) and cultured for indicated times. For some experiments, myoblasts were grown in low serum medium (DMEM + 2% horse serum). Growth factors were added to untransfected and α5-transfected myoblasts in serum-free medium at the time of plating and twice daily at concentrations of insulin (Sigma; 10 μg/ml), bFGF (from S. Hauschka and Sigma; 10 ng/ml), TGF-β (from S. Amgen and Sigma; 10 ng/ml), and TGF-α (Calbiochem; 10 ng/ml), PDGF-BB (Sigma; 20 ng/ml).

Myoblasts were immobilized for a muscle specific marker, muscle α-actinin, to determine the extent of biochemical differentiation and myofibrillar organization in the various transfectants. At the time points indicated, coverslips were washed with PBS and fixed with 3% formaldehyde in PBS for 15 min. Cells were permeabilized with 0.2% Triton X-100 in PBS for 10 min at room temperature, washed, and blocked in 5% goat serum-PBS for 30 min. Cells were incubated with primary antibody, 9A2B8, (a gift of D. Fishman) an mAb against muscle specific α-actinin (at a 1:5 dilution of hybridoma supernatant in 5% goat serum) for 30 min, and then...
with FITC sheep anti-mouse IgG (Cappel, Malvern, PA), rhodamine phal- 
loidin (Molecular Probes), and DAPI (1:2,000 dilution; Sigma) to stain the 
total nuclei for an additional 30 min. Coverslips were washed and 
mounted in medium containing elvanol and p-phenylenediamine. Fluores-
cence was observed on an Axiosplan fluorescence microscope (Carl Zeiss, 
Inc., Thornwood, NY). The degree of morphological differentiation is ex-
pressed as the fusion index, the percentage of total nuclei in myotubes, 
and was scored in three independent experiments for five random fields at 
the indicated time points.

The fraction of proliferating cells was determined by measuring incor-
poration of BrdU by myoblasts either in complete myoblast medium or in 
serum-free medium in the presence or absence of individual growth fac-
tors. Cells were seeded as described above in the appropriate medium and 
grown for 12, 24, 48, or 72 h. BrdU (50 μM in DMEM) was added to cul-
tures for 12 h before fixation at indicated time points. Coverslips were 
fixed for 10 min in 95% ethanol, washed, denatured in 2N HCl for 30 min, 
and immunostained with an anti-BrdU mAb (Sigma) at a 1:750 dilution in 
5% goat serum followed by FITC-sheep anti-mouse IgG and DAPI. The 
percentage of proliferating cells, the fraction of total nuclei immunopositi-
ve for BrdU, was scored for five random fields in three independent ex-
periments. Cell survival for untransfected and α5-transfected myoblasts in 
serum-free medium or in serum-free medium including growth factors is 
expressed as a ratio of the average number of nuclei per field in the pres-
ence or absence of growth factor to the average number of nuclei per field 
in serum-free medium alone after 24 h. The data were calculated for five 
random fields in three independent experiments.

Results

Ectopic Expression of Integrin α Subunits in Primary Muscle

The role of integrins in myogenesis was addressed by ecto-
ptic expression of integrin α subunits in primary quail skeletal muscle cultures. These cells transfect stably with 
high efficiency (DiMario et al., 1993) and most aspects of 
muscle differentiation are faithfully reproduced in culture. We chose initially to express the α5 and α6 subunits of inte-
grin because they are implicated in myogenesis (Blas-
chuk and Holland, 1994; Boettiger et al., 1995; Bronner-
Fraser et al., 1992; Enomoto et al., 1993; Lakonishok et al., 
1992), signal transduction events (Damsky and Werb, 
1992; Jewell et al., 1995; Juliano and Haskill, 1993; Shaw et 
al., 1995) and the control of cell proliferation (Giancotti 
and Ruoslahti, 1990; Sager et al., 1993; Varner et al., 1995).

Replicating, primary quail myoblasts were transfected with 
the expression plasmids, 1654 (Ghattas et al., 1991) or 
PRSVneo (Reszka et al., 1992), containing either the hu-
man α5 cDNA, the chicken α6 cDNA, or a lacZ control 
cDNA as well as a neomycin resistance gene as a selec-
table marker. The lacZ transfection served as a control for 
both neomycin selection and for ectopic expression of a foreign gene. Transfected cells were analyzed for surface 
expression by flow cytometry using a subunit specific anti-
bodies as described in Materials and Methods. The α5-
transfected myoblasts were analyzed with a human α5 spe-
cific mAb, VIF4, while overexpression of the α6 subunit was detected with a polyclonal chicken α6 specific anti-
body, α6ex, which recognizes both the endogenous quail 
α6 subunit and the transfected chicken α6 subunit.

As shown in Fig. 1, both integrin α subunits were effi-
ciently expressed on the cell surface at high levels 48–72 h 
after transfection. The human α5 (ha5) subunit was ex-
pressed in 60–80% of the cells (Fig. 1 A). Similar expres-
sion levels were obtained with both the 1654-α5 and PRS-
Vneo-α5 plasmids. The chicken α6 subunit was initially 
expressed at levels 2–4-fold greater than the endogenous

Figure 1. Ectopic expression of integrin α subunits in primary mus-
cle. Primary quail myoblasts were transfected with the human α5 
(ha5) subunit (A), the chicken α6 (cha6) subunit (B), the human 
α6 (ha6) subunit (C), or antisense chicken α6 (ASα6) (D) and 
analyzed for transient cell surface expression by flow cytometry. All 
subunits are efficiently expressed by 48 h after transfection. Ecto-
ptic integrins were detected with a subunit specific antibodies. 
(A) The ha5 specific mAb, VIF4, does not cross react with un-
transfected myoblasts (UT) and is specific for the transfected 
subunit. (B and D) Untransfected, cha6, or ASα6-transfected 
myoblasts were stained with the chicken α6 specific antibody, 
α6ex, which recognizes both the endogenous quail α6 (qa6) 
subunit and the transfected cha6 subunit. (B) The shift in the cha6 
profile represents the total α6 integrin expressed on the cell sur-
face. (D) Expression of the qa6 subunit is efficiently suppressed 
by ASα6 five days after transfection. A nonspecific rabbit IgG 
(RlgG) was used as a negative fluorescence control on untrans-
fected myoblasts. (C) The 2B7 mAb is specific for the ha6 sub-
unit and does not react with untransfected myoblasts (UT).
The α5 and α6 Integrins Act Reciprocally to Regulate Muscle Proliferation and Differentiation

Ectopic expression of the α5 and α6 integrins produced dramatic as well as contrasting effects on myogenesis, the earliest and most striking of which is the effect on the transition between myoblast proliferation and differentiation. In a rich medium containing a high concentration of horse serum and embryo extract, control, untransfected myoblasts (UT) initially replicate, and after 48 or 72 h, a significant fraction of the cells undergo differentiation, as determined by both biochemical and morphological criteria while the remainder of the cells continue to proliferate. Approximately 50% of the total nuclei are found in multinucleated myotubes by 72 h (Fig. 2 A). The majority of these cells express muscle specific markers, such as muscle α-actinin, which organize into myofibrils in a striated pattern by 72 or 96 h (Fig. 3 A). Myoblasts transfected with a control lacZ plasmid differentiate indistinguishably from UT controls (not shown) demonstrating that expression of a foreign gene per se does not influence proliferation or differentiation.

Ectopic expression of the α5 integrin inhibits differentiation and maintains myoblasts in the proliferative phase. The α5-transfected myoblasts proliferate in clusters to form a monolayer with little detectable fusion or biochemical differentiation. The effect of ectopic α5 expression on myoblast proliferation was quantitated by the ability of both untransfected and α5-transfected myoblasts to incorporate the thymidine analogue 5-bromo-2'-deoxyuridine (BrdU). The percentage of labeled nuclei reflects the fraction of cells that progress through the cell cycle and thus proliferate. As shown in Fig. 4 A, untransfected and α5-transfected myoblasts initially proliferate to a similar extent after 24 h. Whereas the rate of BrdU incorporation decreases to ~50% in the untransfected controls after 48 h, presumably due to withdrawal from the cell cycle by terminal differentiation, 80–90% of α5-transfected myoblasts remain in the proliferative phase. After 72 h the percentage of nuclei in α5-transfected myoblasts that incorporate BrdU decreases, most likely due to density-dependent inhibition of growth. However, as shown in Fig. 2 A and Fig. 3 B, the α5-transfected myoblasts do not differentiate. Fewer than 5% of the α5-transfected myoblasts fuse into myotubes (Fig. 2 A) or express muscle α-actinin (Fig. 3 B) after 72 h in culture. Although the α5-transfected myoblasts do not differentiate, they are myogenic since they express the L4 antigen, a cell surface marker for the myogenic lineage (not shown) (George-Weinstein et al., 1993). Expression of the α6 subunit was also unstable in primary quail myoblasts. The α6 subunit was initially expressed in 80% of G418-resistant cells (Fig. 1 C) at a level comparable to the α5 subunit. However, this expression was lost after about six to seven days in culture (not shown). Thus, the instability of α6 expression appears to be unique to some cell types or primary cells and does not appear to be a DNA subcloning artifact. Therefore, for most experiments, we relied on cell sorting to enrich transient populations which overexpressed chicken α6 or performed experiments with α6 expressing myoblasts during a window of 1–5 d after G418 selection when expression was still present on the cell surface.

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Figure 3. Muscle α-actinin expression and organization in myoblasts transfected with the hα5 subunit or the hα5 subunit with an altered cytoplasmic domain. Untransfected and transfected myoblasts were cultured for 72 h on FN-coated coverslips in complete myoblast medium and immunostained with a muscle α-actinin specific mAb, 9A2B8 (A–C, D, and E). In B' and C', cells were costained for actin with rhodamine phalloidin to mark the location of the cells in B and C. (A) Untransfected myoblasts fuse into myotubes, express muscle α-actinin, and organize it into a striated pattern. (B and B') Ectopic expression of the hα5 integrin inhibits differentiation. Note that muscle α-actinin is not expressed (B) and actin costaining (B') shows that hα5-transfected myoblasts are not fused into myotubes. (C and C') Ectopic expression of a truncated hα5 subunit, α5corexR, which retains the conserved GFFKR region, inhibits differentiation. Muscle α-actinin expression is not detected (C) and the cells do not fuse into myotubes (C'). (D) Myoblasts transfected with the α5ex6ctyo subunit differentiate after 72 h. They fuse into myotubes and express and organize muscle α-actinin in striations. (E) Ectopic expression of an hα5 subunit with a deletion of its entire cytoplasmic domain, α5Δcyto, does not inhibit differentiation. Note the presence of myotubes and muscle α-actinin. However, muscle α-actinin is not organized in clear striations. Bars: (B, B', C, and C') 50 μm; (A, D, and E) 30 μm.

1988). To determine if the effect of ectopic α5 expression on myoblast proliferation and differentiation is specific for the transfected subunit, we expressed a human α5 antisense plasmid containing the full-length human α5 cDNA in an inverted orientation to inhibit the ectopic α5 expression. In FACS enriched cells, human α5 expression was efficiently suppressed (to undetectable levels) by the antisense construct (not shown), and restored a differentiation phenotype to the cells closely resembling that of untransfected myoblasts (not shown).

The inability to obtain a stable population of myoblasts expressing the chicken α6 or human α6 subunits suggested that overexpression of this integrin subunit inhibits cell proliferation. To test this, we determined the ability of myoblasts transiently expressing the hα6 subunit to incorporate BrdU. Under similar growth conditions (density and serum concentration) as the hα5-transfected cells, only 5–10% of myoblasts expressing hα6 incorporate BrdU after 24 h (Fig. 4 B). This contrasts both the untransfected controls (Figure 4, A and B) and the hα5-transfected myoblasts.
blasts initially proliferate similarly for 24 h. After 48 h, ectopic α5 expression maintains myoblasts in the proliferative phase while proliferation of untransfected myoblasts decreases. Proliferation in myoblasts expressing the α5GFFKR remain in the proliferative phase resembling α5-transfected myoblasts.

Myoblasts transfected with the α5Acyto truncation proliferate much like the untransfected controls, (D) Myoblasts expressing a5GFFKR remain in the proliferative phase resembling ha5-transfected myoblasts.

Furthermore, they express and organize muscle α-actinin parallels that observed in untransfected controls cultured on a laminin substrate. At 72 h, 45–50% of untransfected myoblasts fuse into myotubes (Fig. 2 B) and muscle α-actinin is expressed and organized in striations (Fig. 5 A). Myoblasts that overexpress chicken α6 differentiate within 48–72 h after cell sorting. Nearly 40% of the enriched α6-transfected cells fuse into myotubes after 72 h (Fig. 2 B). Furthermore, they express and organize muscle α-actinin into striations (Figure 5 D). Thus, in direct contrast to the ha5 subunit, ectopic α6 expression inhibits proliferation but not differentiation.

Since overexpression of the α6 subunit inhibited myoblast proliferation, we next transfected an antisense (AS) chicken α6 CDNA plasmid to inhibit endogenous quail α6 (qα6) expression. The ASα6 construct reduces surface expression of the qα6 subunit to 75% of normal levels after 5 d (Fig. 1 D). This reduction of α6 expression results in enhanced proliferation and inhibited differentiation; an effect opposite to that of α6 overexpression. As illustrated in Fig. 4 B and C, 90% of transfected cells with reduced α6 expression incorporate BrdU after 24 h, and this rate of incorporation persists for 48 or 72 h. These cells also exhibit inhibited differentiation. Fewer than 5% of the nuclei reside in myotubes (Fig. 2 B) and muscle α-actinin is not expressed in the majority of the cells (Fig. 5 B). 8–10 d after transfection, the level of qα6 expression returns to endogenous levels, and the cells differentiate similarly to UT myoblasts (not shown). Therefore, suppression of quail α6 expression, like ectopic expression of the α5 subunit, inhibits myoblast differentiation resulting in sustained proliferation. The overexpression and antisense results together suggest that specific integrins may be critical in the transition between myoblast proliferation and differentiation and that the relative expression levels, i.e., ratios, of different integrins are important in this decision.

The Effects of Ectopic α5 and α6 Expression Are Mediated by the Cytoplasmic Domains

The contrasting effects of ectopic α5 and α6 expression on proliferation and differentiation demonstrate a specificity for integrin α subunits in regulating muscle differentiation. Since integrin α subunits possess distinct cytoplasmic domains (Sastry and Horwitz, 1993), it is likely that the specificity of signals transmitted by different integrin α subunits resides in the cytoplasmic domains. To test this possibility, the cytoplasmic domains of the human α5 subunit and the chicken α6 subunit were exchanged to make chimeric α subunits, α5α6/6cyto or α6α5/5cyto. The chimeric α subunits were stably expressed on the cell surface as determined by flow cytometry. The α5α6/6cyto subunit was sorted for comparable surface expression levels as the ha5 subunit (Fig. 6 D). The α6α5/5cyto subunit, unlike the chicken

Figure 4. Effect of ectopic α5 (A) and α6 expression (B), ASα6 suppression (B), and cytoplasmic domain alterations (A, C, and D) on myoblast proliferation. Untransfected and transfected myoblasts were grown in complete myoblast medium for 12, 24, 48, and 72 h. Cultures were labeled with 50 μM 5-bromo-2’-deoxyuridine (BrdU) for 12 h before fixation at the indicated time points. The nuclei incorporating BrdU were detected by immunostaining with an anti-BrdU mAb and all nuclei were visualized with DAPI. The percentage of BrdU incorporation was scored from five random fields and represent an average of three independent experiments. The error bars correspond to the standard deviation of percentage of labeled nuclei for different fields. (A) Untransfected (UT) and ha5-transfected myoblasts initially proliferate similarly for 24 h. After 48 h, ectopic α5 expression maintains myoblasts in the proliferative phase while proliferation of untransfected myoblasts decreases. Proliferation in myoblasts expressing the α5GFFKR remain in the proliferative phase resembling ha5-transfected myoblasts.
Figure 5. Muscle α-actinin expression and organization in untransfected myoblasts (A) or myoblasts transfected with the chicken α6 subunit (D), the α6ex/6cyto chimeric subunit (C and E), or ASα6 (B). Untransfected (UT) or transfected myoblasts were cultured on LM-(UT, chicken α6, and α6ex/6cyto) or FN (ASα6)-coated coverslips in complete myoblast medium for indicated times and immunostained for muscle α-actinin (A–C, D and E) or phalloidin (B' and C'). (A) Untransfected cells differentiate and fuse into myotubes after 72 h on an LM substrate. Muscle α-actinin is expressed and organized in striations. (B) Antisense suppression of endogenous α6 expression inhibits differentiation. Muscle α-actinin expression is not detected in 72-h cultures (B) and fusion into myotubes is inhibited (B'). (D) Ectopic expression of the chicken α6 subunit does not inhibit myotube formation or muscle α-actinin expression and organization in 72-h cultures. (C) Expression of a chimeric subunit, α6ex/6cyto, inhibits myogenic differentiation in subconfluent, 48-h cultures. Muscle α-actinin expression (C) and myotube formation (C') are not observed. (E) After 96 h, confluent cultures of α6ex/6cyto-transfected myoblasts differentiate and fuse into myotubes; but muscle α-actinin is not organized in clear striations. Bars: (B, B', C, and C') 50 μm; (A, D, and E) 30 μm.

α6 subunit, was stably expressed and was sorted for an expression level similar to that in myoblasts transiently over-expressing the chicken α6 subunit (Fig. 6 E and F).

Ectopic expression of α5ex/6cyto or α6ex/6cyto produces unique effects on myoblast proliferation and differentiation. Under similar growth conditions, the α5ex/6cyto-transfected myoblasts exhibit inhibited proliferation when compared to myoblasts transfected with the ha5 subunit. BrdU incorporation shows that cells expressing α5ex/6cyto remain in a prolonged lag phase for 48 h compared to both untransfected and ha5-transfected controls in which 80% of the cells proliferate within 24 h (Fig. 4 A). Furthermore, replacement of the α5 cytoplasmic domain with the α6 cytoplasmic domain reverses the inhibition of differentiation observed in ha5-transfected myoblasts. 40% of the α5ex/6cyto-transfected cells fuse into multinucleated myotubes after 72 h (Fig. 2 A). These cells also express muscle α-actinin which organizes in a striated pattern after 72 h (Fig. 3 D). These results demonstrate that the α5ex/6cyto subunit inhibits myoblast proliferation but not differentiation. Thus, the α5ex/6cyto-transfected myoblasts tend to behave similarly, but not identically, to myoblasts overexpressing the α6 subunit.

Myoblasts expressing the reverse construct, α6ex/5cyto, exhibit density-dependent proliferation and differentiation. As shown in Fig. 4 B, 85% of these cells incorporate BrdU after 24 h, and this level is maintained for 48 h. In addition, fewer than 5% of the nuclei reside in myotubes (Fig. 2 B) and muscle α-actinin expression is inhibited (Figure 5 C). If the α6ex/5cyto-transfected myoblasts are
Figure 6. Surface expression levels of the $\alpha_5$ subunit (A), the chicken $\alpha_6$ subunit (E), $\alpha_5$ cytoplasmic domain truncations (B and C), and chimeric subunits $\alpha_5^{cyt}_6$ (D) and $\alpha_6^{ex/5}_6$ (F) in transfected myoblasts used in experiments. Myoblasts were transfected with the pRSVneo plasmid containing the $\alpha_5$ or chicken $\alpha_6$ integrin cDNAs or cytoplasmic domain mutants and selected for comparable expression levels by fluorescence-activated cell sorting (FACS) to normalize receptor numbers for use in experiments. (A) Myoblasts stably expressing the $\alpha_5$ subunit on the surface were sorted by FACS to enrich for a population that was 80-90% positive for $\alpha_5$ expression. Myoblasts transfected with the $\alpha_5^{Aeyto}$ truncation (B), the $\alpha_5^{GFFKR}$ truncation (C), and the $\alpha_5^{ex/6}_6$ chimeric subunit (D) were sorted by FACS for comparable surface expression profiles to that of enriched $\alpha_5$-transfected myoblasts. (F) Myoblasts stably expressing the chimeric subunit, $\alpha_6^{ex/5}_6$, were sorted for similar surface expression as cells transiently overexpressing the chicken $\alpha_6$ subunit (E).

Subcultured, they remain in the proliferative phase for the life of the cells in culture as discussed above for myoblasts transfected with the $\alpha_5$ subunit. However, if these cells are allowed to remain confluent for 24-48 h, they undergo synchronous differentiation and 40% of the nuclei reside in myotubes (Fig. 2 B). While muscle $\alpha$-actinin is expressed, it is not organized in striations even after 96 h (Figure 5 E). This contrasts the untransfected controls (Fig. 5 A) or myoblasts transfected with the chicken $\alpha_6$ subunit (Fig. 5 D) in which muscle $\alpha$-actinin appears stri-
Figure 7. Effect of exogenous growth factors on muscle α-actinin expression and organization in hox5-transfected myoblasts. Untransfected (A) or hox5-transfected myoblasts (B–G) were cultured on FN-coated coverslips under serum-free conditions in the presence (C–G) or absence (A and B) of individual growth factors. At indicated time points, cells were immunostained with the mAb, 9A2B8, which recognizes muscle α-actinin (A–C, E, and G) or double immunostained for muscle α-actinin (D and F) and actin (D' and F') to mark the location of the cells. (A) Untransfected myoblasts fuse into myotubes and express and organize muscle α-actinin into striations after
Table I. Summary of Integrin α Subunit and Cytoplasmic Domain Effects on Muscle Differentiation

| Transfected subunit | Proliferation | Differentiation | Myofibril assembly |
|---------------------|-------------|----------------|------------------|
| human α5            | +           | −              | NA               |
| chicken or human α6 | −           | +              | +                |
| AS α6               | +           | −              | NA               |
| α5α6cyt/5cyt       | −           | +              | +                |
| α6α6cyt/5cyt       | +           | −              | −                |
| α5Δcyt             | +           | −              | −                |
| α5ΔFFKR            | −           | −              | NA               |

+ denotes that cells proliferate, differentiate, or have organized myofibrils. − denotes that cells exhibit greatly inhibited proliferation, differentiation, or myofibril organization. NA, not applicable.

*Differentiate if maintained confluent for 24–48 h, however, muscle α-actinin does not striate.

Integrin Regulation of Muscle Differentiation Is Modulated by Growth Factors

While ectopic expression of the α5 integrin inhibits differentiation, if ho5-transfected myoblasts are allowed to remain as a confluent monolayer for at least one week to ten days, they synchronously fuse into myotubes and express muscle specific proteins (not shown). The spontaneous differentiation of long term, high density cultures of ho5-transfected myoblasts suggests that sustained proliferation and inhibition of differentiation might arise from an altered sensitivity to serum growth factors. Marked differences in serum requirements for the differentiation of untransfected, ho5-transfected, and chicken α6-transfected myoblasts support this hypothesis. The UT and chicken α6-transfected myoblasts exhibit substantial differentiation in a complete medium, containing a high serum concentration and embryo extract (Fig. 2 A and B), as well as in low serum (not shown) or serum-free conditions (UT only; Figs. 7 A and 8 A). In contrast, the ho5-transfected myoblasts terminally differentiate only in a medium containing less than ~2% serum (not shown) including serum-free conditions (Figs. 7 B and 8 A). Thus, a major effect of ectopic α5 expression is an enhanced susceptibility to the proliferation promoting effects of serum growth factors.

We next compared the effects of individual serum growth factors in the decision of the ho5-transfected myoblasts to proliferate or differentiate under serum-free conditions. Addition of different, exogenous growth factors to ho5-transfected myoblasts in serum-free medium resulted in distinct effects on proliferation and differentiation which were not observed in UT controls. These effects are summarized in Table II. In serum-free medium alone, nearly 60% of the ho5-transfected myoblasts fuse into myotubes after 48 h (Fig. 8 A) and express muscle α-actinin. However, in contrast to untransfected cultures where muscle α-actinin organizes in striations (Fig. 7 A), muscle α-actinin in differentiated ho5 cultures is not organized in a striated within 72 h. Thus, myoblasts expressing the α5Δcyt truncation exhibit a phenotype which tends to resemble that of the ho5 subunit. These results further show that the cytoplasmic domain of the α5 subunit positively regulates proliferation whereas the α6 cytoplasmic domain negatively regulates it.

The Conserved GFFKR Region Is Important in α5 Regulation of Differentiation

We next localized active regions of the α5 cytoplasmic domain through ectopic expression of cytoplasmic domain truncation mutants. Since integrin cytoplasmic domains share a highly conserved membrane proximal motif, KXXGFFKR, that is implicated in the regulation of a subunit function (O'Toole et al., 1991), we expressed truncation mutants that retained only this sequence (α5ΔGFFKR) or that deleted the entire cytoplasmic domain (α5Δcyt). Both of these cytoplasmic domain mutants were efficiently and stably expressed on the cell surface as determined by flow cytometry. To normalize surface receptor numbers, myoblasts expressing α5cyt or α5ΔFFKR were sorted by FACS to obtain populations with surface expression profiles comparable to that of the ho5 subunit (Fig. 6, B and C). Ectopic expression of these two deletion mutants resulted in contrasting phenotypes. As shown in Fig. 4 C, the α5Δcyt-transfected myoblasts incorporate BrdU to a similar extent as untransfected and ho5-transfected controls after 24 h. Whereas 80% of myoblasts expressing the ho5 subunit remain in the proliferative phase after 48 h, BrdU incorporation decreases to 50% in myoblasts expressing the α5cyt truncation much like in the untransfected control. After 72 h, myoblasts expressing α5Δcyt fuse into myotubes to a similar extent as untransfected myoblasts (Figure 2 A). They also express muscle α-actinin, however, muscle α-actinin in the resulting myotubes does not organize in striations (Fig. 3 E). Thus, ectopic expression of the α5Δcyt deletion restores differentiation but does not significantly affect the rate of proliferation. On the other hand, myoblasts transfected with the α5ΔGFFKR truncation, behave indistinguishably from ho5-transfected myoblasts. As determined by incorporation of BrdU, 80% of myoblasts expressing α5ΔGFFKR remain in the proliferative phase (Fig. 4 D). Furthermore, fewer than 5% of the cells fuse into myotubes (Fig. 2 A) or express muscle α-actinin (Fig. 3 C). These results show that the ectopic α5 subunit inhibits differentiation and promotes proliferation via its cytoplasmic domain and that the membrane proximal five amino acids are critical in this regulation. The effects of ectopic α5 and α6 expression and cytoplasmic domain alterations on myoblast proliferation, differentiation, and myofibril assembly are summarized in Table I.

48 h in serum-free culture. (B) The ho5-transfected myoblasts fuse into myotubes and express muscle α-actinin, however, unlike the untransfected control, muscle α-actinin is not striated in these cultures. bFGF (D and D’) and TGF-β (F and F’) inhibit muscle α-actinin expression and fusion into myotubes in ho5-transfected myoblasts. TGF-α (C) and PDGF-BB (E) enhance myofibril assembly in differentiated ho5 cultures. After 72 h, muscle α-actinin is organized in striations in contrast to serum-free medium alone (B). (G) Insulin promotes fusion and muscle α-actinin expression in ho5-transfected myoblasts but alters myotube morphology. The myotubes are fat, highly branched and muscle α-actinin organization is impaired. Bars: (D, D’, F, and F’) 70 μm; (A–C, E and G) 20 μm.

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In the presence of bFGF or TGF-β, fewer than 5% of α5-transfected myoblasts fuse into myotubes (Fig. 8 A) or express muscle α-actinin (Fig. 7 D, D', F, F'). Thus, bFGF and TGF-β inhibit the serum-free differentiation of α5-transfected myoblasts. Furthermore, bFGF and TGF-β produce contrasting effects on proliferation of the α5-transfected myoblasts. 25–30% of both untransfected and α5-transfected cells incorporate BrdU in serum-free medium alone (which likely reflects residual growth factor activity) (Fig. 8 B). In contrast, 65% of α5-transfected myoblasts treated with bFGF incorporate BrdU. Hence, the presence of bFGF mimics the mitogenic effects of a rich medium and stimulates proliferation of the α5-transfected myoblasts. Addition of TGF-β, on the other hand, inhibits proliferation of the α5-transfected myoblasts (Fig. 8 B).

Addition of either insulin, TGF-α, or PDGF-BB produces phenotypes distinct from those just described for bFGF or TGF-β. Insulin promotes both proliferation and differentiation of the α5-transfected myoblasts, but has no measurable effect on untransfected cells. As shown in Fig. 8 B, insulin initially stimulates proliferation in 50–60% of α5-transfected myoblasts. After 48 h, the α5-transfected myoblasts differentiate and 70% of the nuclei reside in myotubes (Fig. 8 A). The resulting myotubes however are abnormal; they are short, highly branched and muscle α-actinin is not organized in striations (Fig. 7 G). TGF-α, like insulin, promotes proliferation, although to a lesser extent (Fig. 8 B), as well as differentiation of α5-transfected myoblasts (Fig. 8 A). However, in contrast to insulin or serum-free conditions, TGF-α promotes the organization of muscle α-actinin in striations in the majority of α5-transfected myotubes (Fig. 7 C). Interestingly, among all growth factors tested, only TGF-α stimulates proliferation of the untransfected myoblasts growing under serum-free conditions (Fig. 8 B). PDGF-BB has no effect on proliferation or on the serum-free differentiation of α5-transfected myoblasts (Fig. 8 A and B); however, like TGF-α, it promotes myofibril organization (Fig. 7 E).

While a significant fraction of untransfected and α5-transfected myoblasts differentiated under serum-free conditions, those cells that did not differentiate survived poorly in the absence of serum or growth factors. After 24 h in serum-free culture, ~35–40% of both the untransfected and α5-transfected myoblasts detached from the substrate.

**Figure 8.** Effect of exogenous growth factors on proliferation, differentiation, and survival of untransfected and α5-transfected myoblasts. Untransfected and α5-transfected myoblasts were cultured on FN-coated coverslips under serum-free conditions in the presence or absence of individual growth factors and scored for (A) fusion after 48 h, (B) BrdU incorporation at 24 h, or (C) cell survival at 24 h. Cell survival is expressed as the average number of nuclei per field with or without growth factor relative to serum-free conditions alone. The data were scored from five random fields and are representative of three separate experiments. The error bars correspond to the standard deviations for different fields. (A) The fusion index, the percentage of nuclei residing in myotubes (Fig. 7 B). In the presence of bFGF or TGF-β, fewer than 5% of α5-transfected myoblasts fuse into myotubes (Fig. 8 A) or express muscle α-actinin (Fig. 7 D, D', F, F'). Thus, bFGF and TGF-β inhibit the serum-free differentiation of α5-transfected myoblasts. Furthermore, bFGF and TGF-β produce contrasting effects on proliferation of the α5-transfected myoblasts. 25–30% of both untransfected and α5-transfected cells incorporate BrdU in serum-free medium alone (which likely reflects residual growth factor activity) (Fig. 8 B). In contrast, 65% of α5-transfected myoblasts treated with bFGF incorporate BrdU. Hence, the presence of bFGF mimics the mitogenic effects of a rich medium and stimulates proliferation of the α5-transfected myoblasts. Addition of TGF-β, on the other hand, inhibits proliferation of the α5-transfected myoblasts (Fig. 8 B).

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Table II. Summary of Integrin-Growth Factor Interactions during Muscle Differentiation

| Media condition | Proliferation | Differentiation | Myofibril assembly | Myoblast survival | Proliferation | Differentiation | Myofibril assembly | Myoblast survival |
|----------------|--------------|-----------------|-------------------|-------------------|--------------|----------------|-------------------|-------------------|
| Complete medium | +            | +               | +                 | +                 | +            | -              | NA                | +                 |
| Serum free      | -            | +               | +                 | -                 | -            | +              | -                 | -                 |
| Insulin         | -            | +               | +                 | -                 | +            | +              | -                 | -                 |
| bFGF            | -            | +               | +                 | +                 | +            | +              | +                 | +                 |
| TGF-β           | -            | +               | +                 | -                 | +            | +              | NA                | -                 |
| TGF-α           | +            | +               | +                 | +                 | +            | +              | +                 | +                 |
| PDGF-BB         | -            | +               | +                 | -                 | -            | +              | +                 | -                 |

+, denotes that cells proliferate, differentiate, assemble myofibrils, or survive.
-, denotes that cells display inhibited proliferation, differentiation, myofibril assembly, or survival.
NA, not applicable.

and underwent cell death including nuclear fragmentation and DNA degradation (not shown). The addition of different growth factors to either untransfected myoblasts or ha5-transfected myoblasts had differential effects on myoblast survival. Insulin and bFGF promoted survival of the ha5-transfected myoblasts but not the untransfected myoblasts (Fig. 8 C). TGF-α and TGF-β enhanced the survival of the untransfected myoblasts but not the ha5-transfected myoblasts. PDGF-BB protected neither the untransfected nor the ha5-transfected myoblasts. Taken together, these results demonstrate that growth factors elicit different phenotypes for cell differentiation, proliferation, myofibril organization, and cell survival depending on the integrin background of the cells to which they are added.

**Discussion**

In this study, we addressed the role of integrins in muscle differentiation through ectopic expression of integrin α subunits in primary skeletal muscle. Primary quail muscle is an attractive in vitro system both for the study of differentiation and for the ectopic expression of foreign genes. Since many aspects of muscle differentiation and development are rapidly and faithfully reproduced in these primary cultures, this system enables us to determine the effect of changes in integrin expression at multiple stages of myogenesis. Our results demonstrate the efficient, ectopic expression of integrin α subunits in primary quail myoblasts. The phenotypes we observe support the previous studies of Menko and Boettiger (1987) which suggest that β1 integrins can regulate terminal muscle differentiation. We extend their studies by showing that different integrin α subunits play distinct roles in regulating the transition from proliferation to terminal differentiation and in determining aspects of the differentiated phenotype. These effects appear to result from signaling events mediated by the integrin α subunit cytoplasmic domains. Our data further suggest that the differentiative phenotype is an integrated response to the signals produced by the different integrins expressed on the cell surface and the signals arising from the growth factor environment in which the cells reside. In this context, cell lines, which possess activated signaling pathways, may show responses to different integrins, matrix composition, and growth factors that differ from those in primary cells.

Several previous studies implicate the α5β1 integrin in signaling events that regulate cell proliferation (Giancotti and Ruoslahti, 1990; Varner et al., 1995), differentiation (Adams and Watt, 1990; Boettiger et al., 1995; Hotchin et al., 1993), and apoptosis (Zhang et al., 1995). The α5β1 integrin participates in signal transduction events leading to induction of metalloproteinase expression in rabbit synovial fibroblasts (Werb et al., 1989) and to changes in immediate early gene expression that correlate with proliferation (Varner et al., 1995). Overexpression of the α5 integrin in transformed cell lines suppresses tumorigenicity and anchorage-independent proliferation but promotes proliferation upon substrate attachment (Giancotti and Ruoslahti, 1990; Varner et al., 1995). These findings suggest that the signals mediated by the α5 subunit, which positively signal proliferation in cells adherent to FN and negatively regulate growth in suspension, depend on the state of ligation, i.e., conformation or activation state, of the α5β1 heterodimer (Varner et al., 1995). Our findings support a role for the α5 integrin in promoting anchorage-dependent proliferation. Cell attachment to FN via the α5 integrin also promotes cell survival (Zhang et al., 1995). CHO cells that do not express the α5 subunit undergo apoptosis in the absence of serum. Surprisingly, ectopic expression of the α5 subunit in our system does not spare myoblasts from cell death in serum-free conditions despite the presence of a FN substrate. Thus, cell attachment is not sufficient to protect myoblasts from cell death. Presumably α5 regulation of cell survival is cell-type dependent. However, as discussed below, ectopic α5 expression does affect both myoblast proliferation and survival when myoblasts are grown in the presence of particular growth factors.

The α5β1 integrin also plays an important regulatory role during differentiation. A functional inactivation, resulting in a decreased adhesion to FN and downregulation, of the α5β1 integrin coincides with keratinocyte differentiation (Adams and Watt, 1990; Hotchin et al., 1993). In muscle, α5β1 is subject to regulation early in myogenesis suggesting an involvement in its terminal differentiation (Enomoto et al., 1993; Lakonishok et al., 1992; Blaschuk and Holland, 1994). The α5β1 integrin is expressed in proliferating myoblasts but is downregulated upon induction of terminal differentiation. This observation suggests that continuous, high-level expression of the α5 integrin coin-

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cides with proliferation which is consistent with our observations. There is also evidence that changes in the activation state of the α5 integrin regulate muscle differentiation (Boettiger et al., 1995). Our experiments confirm and extend these previous studies implicating the α5 integrin in myogenesis by demonstrating that the expression level of the α5 subunit can affect the proliferative to differentiative transition and organization of myofibrils.

In contrast to the α5 subunit, considerably less is known regarding the biological function of the α6 integrin. In many systems, the α6 integrin is functionally inactive as a laminin receptor. For example, in macrophages (Shaw et al., 1990) and K562 erythroleukemic cells (Delwel et al., 1993), the adhesive function of α6 requires activation by phorbol esters. In addition, upon attachment of activated macrophages to LM, the α6 integrin participates in signal transduction leading to differential tyrosine phosphorylation of several proteins, which depends on the particular cytoplasmic domain isoform expressed (Shaw et al., 1995). Thus, the α6 integrin is subject to cellular regulation and also acts as a signaling receptor. Our data not only point to a potential role for the α5 integrin in differentiation, they also demonstrate a potential role for the α6 integrin in myogenesis. While ectopic expression of the α5 subunit inhibits differentiation and maintains myoblasts in the proliferative phase, ectopic α6 expression inhibits proliferation but not differentiation. Antisense suppression of endogenous α6 expression inhibits differentiation and promotes proliferation.

Taken together, the effects of ectopic α5 and α6 expression and antisense inhibition of α6 expression on myoblast proliferation and differentiation show that perturbing the existing ratio of α5- and α6-expression affects the decision of myoblasts to proliferate or differentiate. The ratio also appears to contribute to myofibrillar organization since the degree of myofibrillar striation differs in α5- and α6-transfected cells. The opposing effects of α5 and α6-expression on myoblast proliferation and differentiation demonstrate a reciprocity between these two integrin subunits and is consistent with previous studies which show an inverse relationship between α5 and α6 expression during chick embryo development (Bronner-Fraser et al., 1992; Muschler and Horwitz, 1991). However, it is premature to conclude that the ratio of α5/α6 expression, per se, is a physiological regulator of muscle differentiation. We conclude only that changes in integrin ratios can regulate the differentiative state. The relative expression of other integrins also contributes to the proliferative to differentiative transition. Thus, integrin regulation of differentiation is best viewed as an integrated response to the relative expression levels of multiple integrins. An analogous example of complementary signaling is observed with the α5β1 and α4β1 integrins in regulating expression of metalloproteinases in rabbit synovial fibroblasts (Huhntala et al., 1995).

How do these integrins act to regulate differentiation? Several observations suggest that the effects of ectopic α5 and α6 expression are mediated by the α subunit cytoplasmic domain through signal transduction processes. The inhibitory effect of α5p/6GFP expression on myoblast proliferation and the maintenance of the proliferative phase by expression of α6p/5GFP show that the α6 cytoplasmic domain is involved in negative regulation of cell growth whereas the α5 cytoplasmic domain transmits proliferative signals. We also show that the conserved, membrane proximal, GFFKR sequence in the α5 cytoplasmic domain is a critical element in the regulation of differentiation via the α5 subunit. The GFFKR sequence regulates the affinity of the α1β3 integrin for fibrinogen (O'Toole et al., 1991). In our system, the role of receptor activation and ligation in mediating the effects of ectopic α5 or α6 is unclear. Both the α5 and α5GFFKR-transfected myoblasts, which do not differentiate, and the α5Δcyt and the α5p/6GFP-transfected myoblasts which do differentiate, adhere similarly to a FN substrate and organize cell surface FN similarly (Sastry, S., and M. Lakonishok, unpublished results). However, since these cells secrete FN, it is difficult to test the effects of a single ligand on differentiation. It is also possible that ectopic α5 expression leads to a change in the expression of other integrin subunits either by replacement of endogenous α subunits by the ectopic α5 subunit or by the downregulation of another α subunit. However, surface immunoprecipitations of β1 integrins from α5-transfected myoblasts do not reveal major changes in the profile of α subunits that associate with the β1 subunit when compared to those present in untransfected myoblasts. Among specific α subunits for which suitable antibody probes are available, the level of endogenous quail α5, α6, and α3 expression do not change significantly as a result of ectopic α5 expression (Lakonishok, M., and S. Sastry, unpublished results). We do, however, observe a twofold increase in the total amount of surface β1 and a four to fivefold increase in the total amount of surface α5 expressed in the ho5-transfected myoblasts.

Thus, the most likely explanation for our results is that the integrins activate signaling pathways which interact with growth factor signaling pathways. It is interesting to note that v-src- transformed myoblasts possess a phenotype (Alema and Tato, 1987) similar to that of the ho5-transfected myoblasts in our study. Our preliminary studies show significant tyrosine phosphorylation of several proteins with molecular masses in the ranges of 30-34 kD, 60-70 kD, and 120 kD in α5-transfected myoblasts grown in a rich medium but not in untransfected controls (Lakonishok, M., unpublished results). While FAK stands out as an obvious point of convergence between integrin, src-kinases, and growth factor mediated signal transduction pathways (Schlaepfer et al., 1994; Zachary and Rozengurt, 1992), we have not observed changes in its tyrosine phosphorylation that correlate with differentiation. Interestingly, in serum-free conditions, where α5-transfected myoblasts terminally differentiate, the α5 induced tyrosine phosphorylations are suppressed suggesting that α5-mediated signaling depends on the activation of growth factor signaling pathways.

An extensive literature points to growth factors as critical regulators of myogenesis (Florini and Magri, 1989). Our observations demonstrate that growth factor regulation depends on the particular integrins present. This points to an interaction between integrin and growth factor signaling pathways, the consequence of which is that integrin regulation of differentiation depends on the precise growth factor environment and vice versa. For example, the ectopic expression of different integrins shifts the serum response of myoblasts to favor either the prolifera-
tive or differentiative pathway. Ectopic α5 expression enhances myoblast susceptibility to the mitogenic factors in serum whereas ectopic α6 expression abrogates it. Furthermore, ectopic α5 expression alters the response to individual growth factors uniquely to influence differentiation at multiple stages. Similar treatment of untransfected myoblasts does not measurably alter their serum-free differentiation. bFGF, for example, influences the transition from proliferation to differentiation by stimulating proliferation and inhibiting differentiation in the ho5-transfected myoblasts but not in untransfected cells. Insulin, in contrast, promotes both proliferation and differentiation; but the resulting myotubes display an altered morphology and poorly organized myofibrils. PDGF, while having no detectable effect on the decision of α5-transfected myoblasts to proliferate or differentiate, enhances myofibril assembly. TGF-α is unique among the growth factors tested in that it stimulates proliferation, differentiation, and myofibrillar assembly. It produces a phenotype in the α5-transfected myoblasts that most closely resembles untransfected myoblasts grown in a rich medium. The effects of insulin on myotube morphology and TGF-α and PDGF on myofibrillar assembly also demonstrate that these events are regulated, at least in part, by signaling mechanisms and point to a role for integrin-growth factor coupled signaling in muscle morphogenesis. Although the mechanism by which muscle α-actinin becomes striated in the presence of TGF-α or PDGF is unclear, it should be noted that the organization of other cytoskeletal components like talin and myosin heavy chain are not altered by ectopic α5 expression (Lakonishok, M., unpublished results). Finally, it is interesting that the growth factor effects on ho5-transfected, rather than untransfected cells, most closely resemble those described in the literature for muscle cell lines (Florini and Magri, 1989).

The ectopically expressed α5 subunit and growth factors also interact to affect cell survival, a process that is also the result of a signal transduction pathway (Yuan, 1995; Earnshaw, 1995). Ectopic α5 expression does not spare myoblasts from cell death in the absence of serum despite enhanced attachment of the α5-transfected myoblasts to FN compared to untransfected myoblasts. Thus, cell attachment is not sufficient to promote myoblast survival. However, the addition of insulin or bFGF protects ho5-transfected myoblasts from cell death but does not enhance the survival of untransfected myoblasts. In contrast, TGF-α and TGF-β protect the untransfected myoblasts but not the ho5-transfected myoblasts. Therefore, different growth factors differentially influence cell survival of untransfected and ho5-transfected myoblasts, demonstrating further that ectopic α5 expression changes the growth factor response.

Our biological observations complement recent biochemical evidence that demonstrates a coupling between integrin and growth factor signaling pathways (Yamada and Miyamoto, 1995). Integrin engagement is required for PDGF-induced inositol lipid breakdown in fibroblasts (McNamee et al., 1993) and for the association of a novel tyrosine phosphorylated protein with integrin (Bartfeld et al., 1993). In addition, a physical association between IRS-1, a component of the insulin signaling pathway, and the αβ3 integrin after ligation of the insulin receptor has been demonstrated (Vuori and Ruoslahti, 1994). Another recent report shows that cell attachment to fibronectin causes focal adhesion kinase to associate with proteins in the growth factor-activated Ras/MAP kinase signaling pathway (Schlaepfer et al., 1994).

In summary, the results presented here provide clear biological evidence that integrins and growth factors act together to regulate muscle differentiation. Our data lead to the following conclusions about the role of integrins and growth factors in regulating muscle differentiation. First, different integrins initiate characteristic signals to differentially affect proliferation and differentiation. The ratio of the different integrins expressed and their ligation state are the key parameters. Second, the growth factor environment in which the cell resides influences the integrin mediated signals to uniquely regulate differentiation, proliferation, cytoskeletal assembly, and cell survival. Third, in the absence of a mitogenic stimulus, i.e., serum-free conditions, myoblasts differentiate suggesting that differentiation is the default pathway. Those myoblasts which are unable to differentiate undergo cell death. Fourth, the precise cellular phenotype is a combinatorial response resulting from an integration of signals emanating from specific integrins and particular growth factors. Thus, integrins appear in many respects as functionally equivalent to growth factor receptors.

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