Cell-autonomous integrin control of Wnt and Notch signalling during somitogenesis

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SUMMARY
Integrins act at signalling crossroads, and their interactions with other signal transduction pathways are key to the regulation of normal and pathological cell cytoarchitecture and behaviour. Here, we describe a signalling cascade that acts during the formation of the defining segmental features of the vertebrate body – the somites – in which β1-integrin activity regulates epithelialisation by controlling downstream Wnt and Notch activity crucial for somite border formation. Using in vivo transcriptional inhibition in the developing chick embryo, we show that β1-integrin in the anterior presomitic mesoderm activates canonical Wnt signalling in a cell-autonomous, ‘outside-inside’ manner. Signalling is mediated by integrin-linked kinase (ILK), leading to modulation of glycogen synthase kinase 3β (GSK3β) phosphorylation, and activates Notch signalling in the anterior presomitic mesoderm. The two signalling pathways then cooperate to promote somite formation via cMESO1/Mesp2. Our results show that β1-integrin can regulate cell shape and tissue morphogenesis indirectly, by regulation of downstream signalling cascades.

KEY WORDS: Notch, Wnt, Integrin, Signalling, Somitogenesis, Chick

INTRODUCTION
Integrins are trans-membrane proteins that are required for a variety of developmental processes, including cell adhesion, migration, gastrulation and morphogenesis, proliferation and signal transduction. Heterodimers of α and β trans-membrane chains together bind to a variety of extracellular matrix molecules and ligands, including fibronectin for the β1-integrins (Juliano, 2002), thereby modulating interactions between the cell membrane and the cytoskeleton (Legate et al., 2006). Integrin-containing complexes interact with actin filaments and focal adhesion complexes, but also regulate, and are regulated by, receptor tyrosine kinases and other signalling pathways (Hannigan et al., 2005; Legate et al., 2006).

Two modes of integrin signalling have been proposed (Abram and Lowell, 2009). ‘Inside-outside’ signalling is well-described in lymphoid and other systems, and occurs when an intracellular stimulus (from a trans-acting signalling pathway) increases the ligand-binding affinity of integrins, leading to the recruitment of extracellular matrix that can remodel cell shape and tissue organisation (Abram and Lowell, 2009; Legate et al., 2006). ‘Outside-inside’ signalling results when extracellular ligand binding to integrin receptors activates integrin-linked kinase (ILK), a conserved, intracellular kinase-like protein that binds to the cytoplasmic tail of β1-integrin (Hannigan et al., 1996).

One process that appears to rely on integrin activity is segmentation, which is the sequential production of axially repeated balls of epithelial cells (somites) that give rise to vertebrae, skeletal muscles and some of the dermis. Bilateral pairs of somites form at regular intervals by budding off from the anterior of the unsegmented presomitic mesoderm (PSM) that lies on either side of the neural tube (Pourquié, 2001). Regular somite production depends on a molecular oscillator (‘segmentation clock’) that drives cyclic transcription in the posterior PSM (Ozbudak and Pourquié, 2008; Palmeirim et al., 1997).

α5-integrin mutations affect segmentation in both mouse and zebrafish (Jüllich et al., 2005; Koshida et al., 2005; Yang et al., 1999). However, the mutations disrupt different regions in the two animals: zebrafish mutants lack only the first five to seven somites, whereas only posterior somites are affected in mutant mouse embryos. These results suggest that integrin signalling is not obligatory for somitogenesis.

The segmentation phenotype of zebrafish α5-integrin mutant embryos has been explained by an inability to recruit fibronectin ligand as an inside-outside response to Notch signalling, at least in anterior somites (Jüllich et al., 2005). Nevertheless, it remains possible that integrins act by regulating other signalling pathways. Segmentation critically depends on both Notch and Wnt signalling, which are required in the posterior PSM for the segmentation clock and in the anterior PSM for somite differentiation (Aulehla et al., 2008; Dunty et al., 2008; Saga et al., 1997). Integrin signalling has previously been linked to Wnt signalling: in vitro, ILK can phosphorylate and inactivate glycogen synthase kinase 3β (GSK3β), a negatively acting component of the Wnt pathway (Olouni et al., 2006; Sutherland et al., 1993). Interactions between integrin and Notch signalling have also been reported in cultured cells, although with very inconsistent outcomes that have been explained by a diversity of different mechanisms (Campos et al., 2006; Hodkinson et al., 2007).

In this paper, we use the chick embryo to investigate the mechanism of β1-integrin action during somite formation. We show that knockdown of β1-integrin in the PSM abolishes somite formation along the entire body axis, indicating that integrin activity is required for the formation of all chick somites. We
further define an outside-inside signalling pathway in which β1-integrin signals cell-autonomously via ILK to activate Wnt signalling in the anterior PSM. Wnt signalling then activates Notch signalling, and these target pathways act in combination to drive somite boundary formation. These results define a regulatory cascade by which β1-integrin regulates cell and tissue architecture in vivo.

MATERIALS AND METHODS

Eggs

Fertilised chicken eggs (Henry Stewart, Louth, UK) were incubated at 37°C and were staged according to Hamburger and Hamilton (Hamburger and Hamilton, 1951).

Electroporation

Electroporation conditions were based on those described previously (Momose et al., 1999). In summary, DNA plasmids were diluted to 1-2 μg/μl in PBS containing 2% sucrose and mixed with Fast Green for visualisation of the injection site. For electroporations at HH9, DNA was injected in ovo over the anterior primitive streak. Electrodes were placed at either side of the embryo and five 50-msecond pulses of 35V were applied. For electroporations in the node and primitive streak at HH4/5, the negative and positive electrodes were placed above and below the embryo, respectively, and five 50-msecond pulses of 10V were applied.

Embryo culture

Chick embryos were cultured in L15 medium supplemented with 15% foetal calf serum in a roller incubator at 37°C. For pharmacological inhibition of signalling pathways, embryos were cultured for 6 hours in 10-100 μM N-[N-(3,5-difluorophenacetyl)-L-alanyl]-S-phenylglycine t-butyl ester (DAPT), 1 μg/ml recombinant mouse Dkk1 (R&D Systems), 5 mM LiCl, or 200 μM CKI-7 (Sigma-Aldrich).

In situ hybridisation, immunohistochemistry and western blot

Whole-mount in situ hybridisation was carried out as previously described (Henrique et al., 1995). Immunohistochemistry was performed using standard methods with mouse anti-chick fibronectin (B3/D6 and VA1; supernantant 1/5, Developmental Studies Hybridoma Bank), rabbit polyclonal anti-GFP (1/500, Invitrogen/Molecular Probes), and V2E9 monoclonal anti-β1-integrin (Hayashi et al., 1990) (supernantant 1/30, Developmental Studies Hybridoma Bank). The specificity of the anti-β1-integrin antibody was further confirmed using RNAi knockdown. The appropriate Alexa Fluor-conjugated secondary antibodies were used at 1/500 (Invitrogen/Molecular Probe), and final samples mounted in Slowfade Gold Anti-Fading Reagent (Invitrogen/Molecular Probes) and observed under a Zeiss LSM510 confocal microscope. For western blots, anterior PSM from three embryos of each category were dissected, homogenised and lysed in RIPA buffer (Harlow and Lane, 1988). Rabbit polyclonal pS9-GSK3β (AbCam) and monoclonal β-tubulin (Sigma) antibodies were used at 1/1000. Detection was performed using the ECL Plus Western Blotting Detection System (Amersham) according to the manufacturer’s protocol.

Plasmids and morpholino oligonucleotide (MO) knockdown

cDNAs encoding chick β1-integrin and the Notch1 intracellular domain (NICP) were cloned into the pCAGGs-RES-nlsGFP expression vector (Stamataki et al., 2005). Wild-type and mutant forms of Ilk cDNAs and human dnMAML fused to GFP (dnMAML-GFP) were cloned into the pmIWI11 expression vector (Suemori et al., 1990). For RNAi against β1-integrin, 22-nucleotide target sequences were chosen using the GenScript design tool (http://www.genscript.com/ssl-bin/app/maii). Six sequences were cloned into pRFPRNAi plasmids (Das et al., 2006). Plasmids containing the target sequences 5’-GCATCGATCTAAACCGTTTGA-3’ and 5’-GGCTGAATGTTACGATGAAT-3’ were the most efficient at depressing β1-integrin immunostaining in embryos and independently produced the same segmentation phenotype (the phenotype was evident in n=9/25 and n=11/25 electroporated embryos, respectively). A mix of the two plasmids was more efficient in producing the same phenotype (n=12/15). Notch1 RNAi constructs were used as described (Das et al., 2006). Wild-type, S343D, E359K and S343A Ilk cDNAs were obtained from the Dedhar laboratory (British Columbia Cancer Research Centre, Vancouver, Canada), and additional point mutants generated using the QuikChange Mutagenesis Kit (Stratagene) according to the manufacturer’s protocol.

We also knocked down gene expression using blocking MOs, fluorescent versions of which can be introduced into chick embryos by co-electroporation with carrier DNA (Voiculescu et al., 2008). In summary, 250 μM translation-blocking β1-integrin MO (5’-GGCACCCGGTG-GCCCTGTCCGG-3’) or 750 nM splice-blocking Ilk fluorescein MO (5’-ACATCCAGGTCTGCGTACCTCTT3’; Gene Tools) plus 250 μg/ml carrier plasmid DNA were co-electroporated into HH5 embryos as described above. The Ilk MO targets the exon 2-intron 2 junction, preventing excision of intron 2 (149 bases) and causing premature translational termination. We confirmed the presence of intron 2 by RT-PCR on RNA from the anterior PSM of three control-electroporated and three MO-electroporated embryos using forward (exon 2, 5’-TACATGAGGGACAAACTTCG-3’) and reverse (exon 3, 5’-CAGGGAAGGAGACTTTCG-3’) primers.

Single-cell qPCR

Chick embryos were harvested in PBS. Individual anterior PSM cells were isolated from anterior PSM tissue that had been lightly trypsinised into small clumps containing neighbouring RFP-positive and -negative cells. Individual cells were isolated using a glass pipette, seeded in the reverse transcription mix, and frozen in liquid nitrogen.

Single-cell RNA amplifications were performed using previously described two-stage protocols (Brady and Iscove, 1993; Tietjen et al., 2003) with modifications in primer composition and annealing temperatures to improve the reproducibility and to better preserve the relative abundance of transcripts (R. Prajapati, C.R. and D.I.-H., unpublished). In summary, cDNA copies were reverse transcribed using a 39-base primer terminating in d(T3), d(A)-tailed using terminal transferase, and the same primer used to generate second strands. Following two sequential rounds of 25 cycles of symmetric PCR amplification, the product was used as a template for qPCR (Platinum qPCR SYBR Green Supermix, Invitrogen). For primers, see Table S1 in the supplementary material.

RESULTS

Knockdown of β1-integrin disrupts somite formation

Previous studies of ablating β1-integrin, the obligate partner of many α-integrins, have revealed novel roles of αβ1-integrins that were not predicted by studies of individual α subunits (Raghavan et al., 2000). As β1-integrin-null mouse embryos die very early owing to inner cell mass failure and peri-implantation lethality (Stephens et al., 1995), we elected to study β1-integrin function during chick somitogenesis.

Whole-mount immunostaining of chick embryos showed that β1-integrin protein accumulates around each forming and mature somite, especially at the borders (HH10, 10 somites; Fig. 1B,C), and in the anterior, but not in the posterior, PSM (Fig. 1D,E). Expression was also seen in the somitocoel, which is the core of the epithelialised somite (Fig. 1F), and in the basal lamina of the neural tube (Fig. 1B-F). Somitic β1-integrin expression patterns were similar in early and late embryos (e.g. HH19, 38 somites; Fig. 1G), implying that expression is maintained throughout somitogenesis. β1-integrin expression was also observed in the tail region, in particular in the chordonedural hinge region, within which lie the progenitors for axial extension of the embryo (Cambray and Wilson, 2002) (see Fig. S1 in the supplementary material; our unpublished results).
To examine whether β1-integrin is required for chick somitogenesis, we used RNA interference (RNAi) with short-hairpin RNAs (shRNAs) to target the degradation of endogenous transcripts (Das et al., 2006). We introduced plasmid DNA into HH4/5 chick embryos by electroporation (Momose et al., 1999), targeting the cells just posterior to Hensen’s node that generate the PSM and somites (Fig. 1P), and used constructs that also express GFP or RFP for visualising the electroporated cells. In some cases, targeting the cells just posterior to Hensen’s node that generate the transcripts (Das et al., 2006). We introduced plasmid DNA into hairpin RNAs (shRNAs) to target the degradation of endogenous somitogenesis, we used RNA interference (RNAi) with short- segmentations (Q, n=25/25). (T-W) Rescue of somite formation after co-electroporation of β1-integrin RNAi with mouse β1-integrin cDNA (n=12/15), showing that the somitic phenotype is indeed due selectively to knockdown of β1-integrin expression. Yellow lines (Q,R,S,V) mark intersomitic space; yellow arrowheads (R,S) mark the absence of somites on the electroporated right-hand side of the embryo. Stages of embryos: (B-F) HH10, (G) HH20, (P) HH10, (H-O,Q,R,T-W) HH12, (S) HH15. In this and subsequent figures, TOPRO-3 is used to stain nuclei and show somitic organisation. Anterior is to the top in this and subsequent figures. PSM, presomitic mesoderm; P.S., primitive streak; ANT, anterior; POST, posterior; L, left; R, right. Scale bars: 100 μm in B-D; 30 μm in F; 250 μm in G; 300 μm in P; 150 μm in H-J,L-N,Q-W. expression, as shown by rescue of the phenotype by co-expression of mouse β1-integrin transcripts, which are resistant to degradation by the chick-specific shRNAs (Fig. 1T-W; see Fig. S2 in the supplementary material). Somites were only lost following efficient electroporation; individual transfected cells still underwent somitogenesis (Fig. 1K), suggesting that loss of somite formation is not due merely to an inability to epithelialise.

Knocking down β1-integrin transcripts by electroporation of a fluorescent, translation-blocking, antisense morpholino oligonucleotide (MO) (Tucker, 2004) (but not of an unrelated MO) also caused loss of segmentation (see Fig. S2 in the supplementary material). The phenotype was rescued by co-expression of mouse β1-integrin transcripts, showing that it is not due to off-target effects on other transcripts.

Older embryos were equally susceptible to loss of β1-integrin signalling, at least up the stage after which electroporation of the PSM is no longer feasible (~HH13; Fig. 1S). Not only did knocking down β1-integrin disrupt somitogenesis (Fig. 1R,S), but the embryos also suffered axial truncations (see Fig. S1F in the

Fig. 1. Knockdown of β1-integrin expression disrupts normal somite formation. (A) Schematic of chicken embryo. (B, C) β1-integrin protein (red) is present in the borders of all somites, including the anterior-most (B) and newly formed (C) somites. (D) Expression of β1-integrin is observed in the anterior (white arrow) but not in the posterior (yellow arrow) PSM. (E) Higher magnification of the anterior PSM shown in D. (F) β1-integrin expression is also detected in the somitocell of epithelial somites (arrowhead). (G) Expression in the somites persists at later stages of development. (H-J) Cells that have been electroporated with RNAi vector (red) do not express β1-integrin (green); n=15/15. (K) Cells electroporated with RNAi vector can be incorporated into the somite epithelium. (L-N) Knockdown of β1-integrin by RNAi results in defective fibronectin expression (green) in the segmental plate; n=10/10. Fibronectin expression where somites should have formed (M, arrow; the yellow arrowhead marks the non-electroporated side) is identical to that in the unsegmented PSM (white arrowhead). (O) Normal expression of fibronectin in the anterior PSM and in somite 1 in embryo electroporated with ineffective RNAi construct on both sides. (P) GFP expression 24 hours after electroporation of the anterior primitive streak of an HH4/5 embryo with control GFP construct (thus targeting both embryo sides), showing efficiency of electroporation. (Q-S) Following β1-integrin RNAi treatment, somites do not form (arrowheads). This is the case for both the anterior-most (R, n=10/22) and posterior-most (S, n=12/15) somites. An unrelated shRNA has no effect on somite formation (Q, n=25/25). Rescue of somite formation after co-electroporation of β1-integrin RNAi with mouse β1-integrin cDNA (n=12/15), showing that the somitic phenotype is indeed due selectively to knockdown of β1-integrin expression. Yellow lines (Q,R,S,V) mark intersomitic space; yellow arrowheads (R,S) mark the absence of somites on the electroporated right-hand side of the embryo. Stages of embryos: (B-F) HH10, (G) HH20, (P) HH10, (H-O,Q,R,T-W) HH12, (S) HH15. In this and subsequent figures, TOPRO-3 is used to stain nuclei and show somitic organisation. Anterior is to the top in this and subsequent figures. PSM, presomitic mesoderm; P.S., primitive streak; ANT, anterior; POST, posterior; L, left; R, right. Scale bars: 100 μm in B-D; 30 μm in F; 250 μm in G; 300 μm in P; 150 μm in H-J,L-N,Q-W.
supplementary material). These results indicate that integrins are required for the generation of all chick somites and also for the maintenance of axial extension.

**β1-integrin expression is independent of active Wnt and Notch signalling**

It has been proposed that integrin signalling acts during zebrafish somitogenesis to mediate epithelialisation in response to the Notch and Wnt signalling pathways that are key in regulating and maintaining somitogenesis (Aulehla et al., 2008; Barrantes et al., 1999; Dunty et al., 2008; Jülich et al., 2005; Jülich et al., 2009; Koshida et al., 2005; Takahashi et al., 2000). Both these pathways lead to transcriptional activation of target genes. Notch acts via an activator complex that includes its proteolytically cleaved intracellular domain (N\textsuperscript{ICD}) (Schroeter et al., 1998). Wnt signalling occurs via nuclear β-catenin complexed with the DNA-binding factor Lef1/Tcf (Behrens et al., 1996; Huber et al., 1996).

Using DNA electroporation, we showed that β1-integrin expression in the anterior PSM is not a target of Notch signalling in the chick. β1-integrin expression was unaffected in cells expressing a dominant-negative form of mastermind-like (dnMAML), a strong inhibitor of the Notch pathway (Maillard et al., 2004) (compare the neighbouring electroporated and non-electroporated cells in Fig. 2A,B). Nor was β1-integrin expression affected by reducing NOTCH1 activity using constructs driving Notch1 RNAi (Das et al., 2006), nor by expressing DELTA1\textsuperscript{DN}, a cell-autonomous, dominant-negative form of the DELTA1 ligand (Henrique et al., 1997) (Fig. 2C-F), and nor by hyperactivating signalling via N\textsuperscript{ICD} (Fig. 2G,H).

β1-integrin expression does not depend on Wnt signalling. β1-integrin levels were unaffected by inhibiting Wnt signalling [with CKI-7 (Fig. 2I) or dickkopf 1 (Dkk1; not shown)] (Glinka et al., 1998; Peters et al., 1999), or by treating embryos with LiCl, which renders Wnt signalling constitutive. These respective treatments inhibit and enhance transcription of Lef1, a Wnt target gene, in the anterior PSM (Gibb et al., 2009; Olivera-Martínez and Storey, 2007) (Fig. 2I; Fig. 3G,H) and other tissues (Driskell et al., 2007; Driskell et al., 2004).

**β1-integrin acts upstream of canonical Wnt signalling in the anterior PSM and acts cell-autonomously**

The lack of somitogenesis in β1-integrin knockdown embryos might be due to a failure of the segmentation oscillator, or because somites are not formed or maintained. The first of these alternatives seems unlikely, as β1-integrin overexpression did not alter the cycling periodicity of the clock target gene lunatic fringe (Lfrng) (see Fig. S3J,K in the supplementary material); the effects of β1-integrin knockdown are masked by the loss of Notch signalling expression (see below).

We saw no evidence that somites are formed initially and then decay. To confirm this, we examined expression of the bHLH transcription factor cMESO1 (also known as Mesp2 in mouse) (Buchberger et al., 1998; Saga et al., 1997), which is required for somite border formation and is expressed in the prospective anterior compartment before somites are established (Morimoto et al., 2005). cMesO1 transcription was downregulated following β1-integrin knockdown by RNAi or MO treatment (Fig. 3B,D), and restored by co-expression of knockdown-resistant β1-integrin transcripts (Fig. 3C,E). Thus, β1-integrin activity is required to establish somitic territories in the anterior PSM, the domain of β1-integrin expression.

Somite patterning might depend on inside-outside modulation of β1-integrin ligand-binding affinity, as previously proposed to explain genetic interactions between notch and α5-integrin during zebrafish somitogenesis (Jülich et al., 2005). According to this model, Notch signalling enhances integrin ligand-binding affinity to regulate cell adhesivity and shape during epithelialisation. Such regulation of integrin signalling by N\textsuperscript{ICD} has also been proposed to occur in cultured cells (ex vivo) (Hodkinson et al., 2007). Alternatively, a ligand–β1-integrin complex might lie upstream of pathways that regulate somite differentiation and boundary formation, such as Wnt signalling. Indeed, we found that knocking down β1-integrin by RNAi or MO reduces transcription of the Wnt target Lef1 in the anterior PSM (Fig. 3J,L), and that overexpressing
β1-integrin enhances Lef1 expression (Fig. 3I). The specificity of these effects was demonstrated by the inactivity of unrelated shRNAs (Fig. 3A; data not shown) and by the restoration of Lef1 expression in knockdown embryos that co-express mouse β1-integrin cDNA (Fig. 3K,M). These results show that β1-integrin signalling activates Wnt signalling in the chick anterior PSM.

Such an outside-inside signalling mechanism implies that β1-integrin acts cell-autonomously in regulating Wnt signalling activity. We assayed cell-autonomy using single-cell quantitative RT-PCR (qPCR) on individual cells following electroporation and neighbouring cells. Constructs that modulate β1-integrin expression were introduced into the right-hand side of HH9 embryos. Single electroporated (fluorescent) and neighbouring non-electroporated cells were recovered from small mixed cell clumps, and single control cells were isolated from the opposite, non-electroporated side (see later). For each class of individual cells (fluorescent cells, non-electroporated neighbours, and contralateral PSM control cells), transcripts were amplified so as to preserve their relative abundance (see Materials and methods). Levels of Lef1 and of the control transcripts of Tbp and Ymhaz (which encode TATA-binding protein and tyrosine 3/tryptophan 5-monoxygenase activation protein, respectively) were then measured using qPCR.

Lef1 responded cell-autonomously to modulation of β1-integrin expression: Lef1 expression was reduced by 85% in β1-integrin knockdown cells and raised 4-fold in β1-integrin-overexpressing cells (Fig. 3N,O). These treatments did not affect Lef1 levels in adjacent and contralateral unelectroporated cells, and levels of control Tbp and Ymhaz transcripts were also unaffected. Thus, β1-integrin acts cell-autonomously in regulating Wnt signalling activity in the chick anterior PSM.

Integrin signalling via integrin-linked kinase is required for Wnt signalling in the anterior PSM

As outside-inside β1-integrin signalling is largely mediated by ILK, we examined the effects of modulating its activity on somite formation. First, we reduced ILK activity by expressing the dominant-negative ILK mutants E359K and S343A (Novak et al., 1998; Persad et al., 2000). E359K (and S343A, not shown) disrupted segmentation (Fig. 4A,B) and decreased Lef1 expression, respectively. (K) Lef1 expression is restored when mouse β1-integrin expression plasmid is co-electroporated with RNAi knockdown plasmid. (L,M) The same results are obtained when an MO against β1-integrin is used. (N,O) qPCR for Lef1 on individual cells following β1-integrin RNAi (N) or overexpression (O). **, P<0.01; Student’s t-test. Error bars indicate s.d. from three independent experimental repeats.

The same results were obtained when ILK expression was reduced by electroporation of a splice-blocking MO that inhibits the production of mature Ilk mRNA (Fig. 4C). Segmentation and Lef1 expression were disrupted (Fig. 4C,I) in these embryos, and restored were by co-expression of MO-insensitive human ILK cDNA (Fig. 4J,K), showing that endogenous ILK activity is necessary for somite formation and Wnt activity. In the converse experiment, overexpression of wild-type ILK or the constitutively active S343D ILK mutant resulted in Lef1 upregulation (Fig. 4E,F).

We confirmed that integrin requirement in somite formation and regulation of Wnt signalling in the anterior PSM proceed via ILK, by showing that ectopic ILK activity is epistatic to loss of β1-
integrin activity. Thus, expressing the constitutively active mutant S343D (Legate et al., 2006) restored somite formation and cMeso1 and Left1 expression to β1-integrin knockdown embryos (Fig. 4L).

**Integrin signalling modulates phosphorylation of GSK3β**

One mechanism by which ILK might affect Wnt signalling is via GSK3β, an inhibitor of Wnt signalling that phosphorylates and destabilises cytoplasmic β-catenin so that it is unable to activate transcription (Hart et al., 1998). ILK can phosphorylate GSK3β on Ser9 in vitro (Maydan et al., 2010; Sutherland et al., 1993) and, directly or indirectly, ex vivo (Legate et al., 2006; Marotta et al., 2001). Levels of phospho-Ser9-GSK3β, as measured on western blots, were indeed elevated in the PSM of embryos incubated in the GSK3β inhibitor LiCl (Fig. 4M).

Levels of phospho-Ser9-GSK3β in the anterior PSM were sensitive to integrin signalling and inversely correlated with Wnt signalling activity, being increased following overexpression of β1-integrin and reduced by β1-integrin knockdown or expression of dominant-negative ILK (Fig. 4M). Phosphorylation levels were also increased by expression of ectopic wild-type ILK or constitutively active S343D. Inhibition via phosphorylation of GSK3β is necessary for integrin/ILK action and Wnt signalling during segmentation, as a constitutive, non-phosphorylatable form of the enzyme, Xenopus S9A-GSK3β (Zhang et al., 2003), blocked segmentation (data not shown) and Left1 expression in both wild-type embryos and those expressing constitutive ILK (Fig. 4N,O).

We then tested whether ILK activity during segmentation depends on its kinase-like domain, in particular, on lysine 220, a conserved residue required for kinases to cleave ATP. We electroporated into the PSM constructs that express the ILK mutants K220A and K220M, which should not be able to co-electroporate into the PSM (Legate et al., 2006). Expression of K220A or K220M ILK (Fig. 4M) resulted in downregulation of Left1 expression (n=6/12) even in the presence of the S343D constitutively active form of ILK (O, n=9/12). HH4/5 embryos were electroporated in the anterior primitive streak, thus targeting both sides. Arrowheads (A,C,K) indicate the bilateral somites. Asterisks, anterior PSM.

**Notch signalling also depends on β1-integrin activity**

We found that β1-integrin activity also regulates Notch signalling, the other major signalling pathway associated with somite differentiation. Expression of several Notch signalling components (Notch1, Delta1) and targets (Lfng, Hairy2) was depressed...
following β1-integrin knockdown by either RNAi or antisense MO treatment (Fig. 5B,D,F,H; see Fig. S5A-D in the supplementary material), and β1-integrin overexpression led to enhanced Notch1 and Delta1 expression and increased Notch signalling (Fig. 5C,E,G,I). As expected, modulating ILK activity affected Notch expression in individual cells (Fig. 5K,L). In the complementary experiment, constitutively active S343D-ILK was unable to upregulate Notch target genes in the anterior PSM (Fig. 6A; see Fig. S5G in the supplementary material), and Lfng expression was restored to control levels when Wnt ligand binding was inhibited by treating embryos with Dkk1 (compare Fig. 4F with Fig. 6P-U). This result shows that ILK acts upstream of Wnt signalling in regulating Notch signalling in the PSM (Harada et al., 1999). This result shows that ILK acts upstream of Wnt signalling in regulating Notch signalling in the PSM.

ILK regulates Notch signalling via the Wnt signalling pathway

The above results could reflect independent regulation of Wnt and Notch activities by β1-integrin/ILK signalling or an upstream effect of Wnt signalling on Notch (Hofmann et al., 2004). In the latter case, one might expect that expressing a constitutively active form of β-catenin would restore Notch signalling to embryos in which ILK activity is inhibited.

Inhibition of ILK signalling resulted in downregulation of the Notch target Lfng in the anterior PSM (Fig. 6A; see Fig. S5G in the supplementary material). However, Lfng expression was restored by co-expressing an N-terminally truncated form of β-catenin (β-Cat^N) that activates transcription constitutively (Fig. 6B,C) (Harada et al., 1999). This result shows that ILK acts upstream of Wnt signalling in regulating Notch signalling in the PSM. Wnt signalling in the PSM still depends on an active Wnt ligand-receptor interaction, even when integrin signalling is constitutive. Constitutively active S343D-ILK was unable to upregulate Lfng or Left expression when Wnt ligand binding was inhibited by treating embryos with Dkk1 (compare Fig. 4F with Fig. 6P-U).

Contrary to our model, it has recently been reported that inhibiting Notch signalling via the γ-secretase inhibitor DAPT leads to loss of Wnt signalling as marked by Left expression (Gibb et al., 2009), suggesting that Notch signalling regulates the Wnt pathway. In our hands, we found that Left expression is only inhibited by extreme doses of DAPT (100 μg/μl), at least 10-fold higher than...
Wnt and Notch signalling cooperate in somite border formation

β1-integrin knockdown embryos fail to express cMeso1 (Fig. 3B,D) in the anterior compartment of presomite –1, indicating that their lack of somites is due to a failure to establish somite boundaries. However, the cells still retained the appropriate mesenchymal identity, expressing the PSM marker Tbx6 (Fig. 6E). Tbx6 has previously been shown to be a Wnt target in the mouse PSM (Dunty et al., 2008). Perhaps knockdown leaves sufficient residual Wnt activity to maintain Tbx6 expression, although we cannot exclude the possibility that there are distinct modes of regulating Tbx6 expression in mouse and chick.

cMeso1 expression depends on both Wnt and Notch activity in the anterior PSM, as expression was lost in embryos incubated in either Dkk1 or DAPT to inhibit the respective pathways (Fig. 6F-H). Wnt activation of cMeso1 might be indirect, being mediated by Notch activity. Alternatively, the two pathways could act on cMeso1 in combination. To distinguish between these mechanisms, we examined whether constitutive activation of Wnt or Notch signalling could restore cMeso1 expression in β1-integrin knockdown embryos. Activating either pathway alone (via NICD or β-CatΔN) caused only very weak cMeso1 expression (Fig. 6K-N), but higher-level expression was achieved when both pathways were activated (Fig. 6O). Thus, the Wnt and Notch signalling pathways collaborate downstream of β1-integrin signalling in chick somite border formation.

DISCUSSION

Previous data have implicated integrin signalling in segmentation, one suggestion being to control cell adhesion properties that contribute to the maintenance of intersomitic borders (Jülich et al., 2005; Koshida et al., 2005; Yang et al., 1999). Our studies of chick somitogenesis reveal that β1-integrin signalling in the anterior PSM acts to establish somite boundaries by regulating other signalling pathways. Signalling via ILK directs phosphorylation of GSK3β, which in turn preserves Wnt and, thereby, Notch signalling. Together, these drive somite compartmentalisation and boundary formation.

Although α5-integrin activity only appears necessary for the formation of subsets of somites in zebrafish and mouse (Jülich et al., 2005; Koshida et al., 2005; Yang et al., 1999), we find that β1-integrin is required essentially throughout chick somitogenesis. This is probably also true in the mouse in which the candidate ligand, fibronectin, is required to form somites (George et al., 1993). Perhaps a different α subunit partner substitutes in forming the α5-independent somites.

The utilisation of specific integrin subunits and ligands during somitogenesis seems to vary between species, particularly between zebrafish and higher vertebrates. Zebrafish and mice differ in their α5 requirement, and also in the necessity for fibronectin activity, which is essential for somite formation in the mouse but required only for the maintenance of somite boundaries in zebrafish (Koshida et al., 2005). loc (ilk) mutant fish lack a segmentation phenotype (Postel et al., 2008). These differences might be due to compensation by paralogues or related genes that are lacking in the chick or mouse.

Wnt and Notch signalling activities are sensitive to modulation of β1-integrin expression (Figs 3, 5), but not vice versa (Fig. 2), indicating that β1-integrin signalling lies upstream of Notch and in the chick anterior PSM, and that reduced Lef1 expression at high drug concentrations is probably due to interference with other gene pathways.
Integrin signalling and segmentation

Wnt activity in the chick anterior PSM. Wnt signalling appears to be regulated by β1-integrin/ILK, but still in a ligand-dependent manner, being blocked by Dkk1, which acts by interfering with Wnt ligand binding (Bafico et al., 2001; Mao et al., 2001; Semenov et al., 2001).

Inhibiting Notch signalling does not affect Wnt signalling (see Fig. 6B in the supplementary material). Rather, Notch is a target of Wnt: reduced β-catenin function in the PSM of β1-integrin knockdown embryos leads to downregulation of the Notch targets Hairy2 and Lfng (Fig. 5H,F; see Fig. S5B,D in the supplementary material), which is due, at least in part, to reduced transcription of Notch1 and Delta1 (Fig. 5B,D). Evidence for direct regulation of mouse Delta1 expression by Wnt has been described previously, including the presence of multiple Lef1 binding sites in its promoter and the defects in mouse somitogenesis caused by mutating Lef1 (Galcon et al., 2004). Although β1-integrin could also regulate NICD activity directly, as proposed for neural stem cells (Campos et al., 2006), such a mechanism would have to be secondary to regulation via Wnt/β-catenin.

A series of epistasis experiments support the above model. Lef1 expression is restored in β1-integrin knockdown embryos that express constitutive ILK (Fig. 4L). β-Cat(Δ) expression restores Lfng expression in embryos expressing dominant-negative ILK (Fig. 6B).

Levels of phospho-Ser9-GSK3β in the anterior PSM correlate with Wnt signalling activity during segmentation, being reduced by knocking down β1-integrin or by expression of dominant-negative forms of ILK, and being enhanced by expression of wild-type or constitutive ILK (Fig. 4M; see Fig. S4 in the supplementary material). These phosphorylation changes are linked with effects on Wnt signalling: Lef1 expression is lost in Ilkconst embryos expressing the constitutive, non-phosphorylatable S9A-GSK3β mutant (Fig. 4O).

One interpretation of our results is that ILK directly phosphorylates and inactivates GSK3β during segmentation. Indeed, we find that the kinase-like domain is important for ILK activity in vivo; mutating K220 in ILK so that it can no longer bind ATP efficiently renders the protein dominant negative (see Fig. S4 in the supplementary material). This explanation is also consistent with a recent study showing that ILK is a bona fide serine/threonine protein kinase that phosphorylates GSK3β in vitro (Maydan et al., 2010).

However, the ILK kinase domain also behaves as a protein-protein binding interface (Fukuda et al., 2009; Legate et al., 2006; Wickström et al., 2010), and several lines of evidence argue for this being its major mode of action. Mutation of the putative ATP-binding site of ILK in Drosophila, mice and worms supports almost normal development (Lange et al., 2009; Mackinson et al., 2002; Zervas et al., 2001). Also, although ILK can phosphorylate GSK3β on Ser9 in vitro, this modification does not necessarily inactivate ILK in vivo; S9A-GSK3β transgenic mice appear to develop normally (McManus et al., 2005).

Thus, we cannot exclude the possibility that ILK acts indirectly on GSK3β during segmentation, e.g. as a protein adapter. Our results also leave open the possibility that ILK affects Wnt signalling in additional ways (e.g. by directly modulating the nuclear localisation of β-catenin) (Oloumi et al., 2006). Indeed, ILK might have different modes of action in different tissue contexts.

The posterior PSM differs from the anterior in several respects. Levels of β-catenin are higher (Aulehla et al., 2008), although levels in the anterior must still be sufficient to support the anterior expression of Lef1 (Gibb et al., 2009; Olivera-Martinez and Storey, 2007) and Rippy2 (Bris et al., 2007). Genetic regulatory interactions also differ between the two domains (Morales et al., 2002; Morimoto et al., 2005), presumably due in part to combinatorial interactions between signalling pathways and regionalised accessory factors that together determine regionally restricted outcomes such as the Wnt responsiveness of Lef1 transcription (Fig. 3G,H). Thus, our studies make no predictions about how β1-integrin, Wnt and Notch signalling interact in the posterior PSM.

Jülich and co-workers have proposed a contrasting model for somite formation in which Notch signalling enhances the affinity of α5/β1 receptors for binding their fibronectin ligand (Jülich et al., 2005; Jülich et al., 2009). Such an inside-outside signalling model might predict that modulating Notch signalling would alter the efficiency of ligand accumulation and integrin signalling, and should thereby affect Wnt signalling. However, blocking Notch signalling with low doses of DAPT does not affect fibronectin accumulation or Lef1 transcription (see Fig. 6B-E,F in the supplementary material), and NICD electroporation has no effect on the levels of phospho-Ser9-GSK3β (see Fig. 6D in the supplementary material), indicating that signalling by Wnt, and hence by β1-integrin, lies upstream of that by Notch.

Somite compartmentalisation and boundary formation appear to rely on Wnt and Notch acting together. Blocking either pathway inhibits somite formation and the cMes01/Mesp2 expression that prefigures somite compartmentalisation and boundary formation (Fig. 6G,H). cMes01 expression is efficiently restored in β1-integrin knockdown embryos only by co-activation of both Wnt and Notch pathways (Fig. 6O). This result is consistent with studies showing that mouse Mesp2 is regulated by Wnt activity (Dunty et al., 2008). As the role of Mesp2 during mouse somitogenesis is, at least in part, to negatively regulate Notch signalling (Morimoto et al., 2005), our results indicate that Mesp2 acts both upstream and downstream of Notch activity in establishing somitic boundaries.

Integrin may act by modulating Wnt and Notch activities in other contexts, e.g. in the axial extension that accompanies segmentation. Interfering with β1-integrin activity leads to truncated embryos (see Fig. S1F,H,J in the supplementary material) that resemble those caused by reduced Wnt and Notch activity (Dunty et al., 2008; Huppert et al., 2005; Takada et al., 1994). Integrin signalling might also target these pathways to promote axial cell proliferation.

Somitogenesis provides an example of outside-inside integrin signalling regulating cell epithelialisation via a signal cascade. Nevertheless, we do not exclude a second, later role for inside-outside integrin signalling, e.g. in somite maintenance and in regulating Eph/ephrin signalling (Durbin et al., 2000; Watanabe et al., 2009). Our results showing that β1-integrin activity lies upstream of Wnt and Notch in primitive presomites do not preclude integrins acting downstream of Notch in forming or formed somites (Nakajima et al., 2006).

Integrin regulation of Wnt signalling is likely to be a recurrent theme during animal development; tissues in which Notch is a Wnt target might recapitulate the signalling network that we have defined for the anterior PSM. Other tissues might use part or variants of the cascade. Genetic studies have demonstrated related Notch and integrin mutant phenotypes in vascular development (Karsan, 2008; Leong et al., 2002), suggesting that these signalling pathways cross-regulate each other. Elevated ILK expression and activity are associated with a variety of cancers in humans (Ahmed et al., 2003; Bravou et al., 2003; Graff et al., 2001), and ILK levels...
and activity correlate with β-catenin-dependent transcription and with human colon tumour grade progression (Bravou et al., 2006; McDonald et al., 2008). In leukaemic cells, ILK activity stimulates Notch1 and Has1 expression and promotes phosphorylation of GSK3β (Tabe et al., 2007). Thus, Notch and Wnt dysregulation in cancer might be linked to excessive integrin signalling.

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Competing interests statement

The authors declare no competing financial interests.

Supplementary material

Supplementary material for this article is available at http://dev.biologists.org/cgi/suppl/displ...dc1

References


Integrin signalling and segmentation


A

B

C

D

Control

\[\text{\textbf{E}}\]

\[\text{\textbf{F}}\]

\[\text{\textbf{G}}\]

\[\text{\textbf{H}}\]

\[\text{\textbf{I}}\]

\[\text{\textbf{J}}\]

\[\text{\textbf{β1-integrin RNAi}}\]

\[\text{\textbf{St.18 HH}}\]

\[\text{\textbf{St.15 HH}}\]

\[\text{\textbf{St.15 HH}}\]

\[\text{\textbf{Fgf8}}\]

\[\text{\textbf{T}}\]
A

mouse
chicken
Xenopus
zebrafish
human

mouse
chicken
Xenopus
zebrafish
human

B

Fluo

C

Liss

D

E

TOPRO-3
Liss
[Mouse $\beta$-integrin]
Merge
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<th>β1-integrin misexpression</th>
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1-integrin misexpression
A - Control
B - wt ILK
C - K220A ILK
D - K220M ILK
E - K220A S343D ILK
F - K220M S343D ILK

G

Control  WT ILK  K220A ILK  K220M ILK  K220A S343D  K220M S343D

PhosphoS9-GSK3β
GSK3β
γ-tubulin
S343D  ILK
E359K  ILK
Control Morpholino
β1-integrin MO

Lfng
hairy2

Notch1
Delta1
Lfng
cMeso-1

E359K ILK

I
J
K
L

I

J

K

L

Control Morpholino
β1-integrin MO

Lfng
hairy2

Notch1
Delta1
Lfng
cMeso-1

E359K ILK

I
J
K
L

I

J

K

L
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**D**

- Control/GFP
- NICD

- phospho-Ser9-Gsk3β
- γ-tubulin

**E**

- FN

**F**

- FN
### Table S1. Primer sequences (5' to 3') for single-cell qPCR

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