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Mechanoregulation of Proliferation▽

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The proliferation of all nontransformed adherent cells is dependent upon the development of mechanical tension within the cell; however, little is known about the mechanisms by which signals regulated by mechanical tension are integrated with those regulated by growth factors. We show here that Skp2, a component of a ubiquitin ligase complex that mediates the degradation of several proteins that inhibit proliferation, is upregulated when increased mechanical tension develops in intact smooth muscle and that its upregulation is critical for the smooth muscle proliferative response to increased mechanical tension. Notably, whereas growth factors regulate Skp2 at the level of protein stability, we found that mechanical tension regulates Skp2 at the transcriptional level. Importantly, we demonstrate that the calcium-regulated transcription factor NFATc1 is a critical mediator of the effect of increased mechanical tension on Skp2 transcription. These findings identify Skp2 as a node at which signals from mechanical tension and growth factors are integrated to regulate proliferation, and they define calcium-NFAT-Skp2 signaling as a critical pathway in the mechanoregulation of proliferation.

Cellular proliferation is regulated by (i) soluble factors, (ii) adhesion to the extracellular matrix, and (iii) the mechanical tension within the cytoskeleton. Although most studies of the regulation of proliferation have focused on the role of soluble factors and adhesion, it is clear that the role of the mechanical tension within the cytoskeleton is of equal importance. In fact, the proliferation of all nontransformed adherent cells is dependent upon the development of mechanical tension (21).

The level of mechanical tension within the cytoskeleton is determined by three factors: (i) the tractional force generated by the cytoskeleton, (ii) the compliance of the extracellular matrix, and (iii) any pulling force transmitted through the extracellular matrix to the cell. These three factors are likely to have a critical regulatory role in every nonhematologic process in which proliferation occurs. Indeed, it has been noted that the sharp differences in the tissue patterns that arise across distances of less than a micrometer during organogenesis, tissue remodeling, and tissue repair cannot be attributed solely to gradients of soluble growth factors. Instead, it has been proposed that it is the differential regulation of proliferation by localized differences in mechanical tension that in large part sculpts the micromorphology of developing, remodeling, and repairing tissues (21). Although many of the "upstream" components of the signal transduction pathways that serve to mediate the mechanoregulation of proliferation, such as integrins, focal adhesion kinase, and the small GTPases RhoA and Rac, have been characterized (2), there is little known about those components that serve to couple mechanical signaling directly to the central cell cycle regulatory machinery.

To begin to identify such "downstream" components of the signal transduction pathways that mediate the mechanoregulation of proliferation, we used two complementary systems: (i) a tissue culture system in which the level of mechanical tension developed by contractile cells in a three-dimensional collagen matrix is varied by altering the compliance of the matrix and (ii) a live rodent system in which the level of mechanical tension within an intact smooth muscle layer is varied by altering the resistance to the contraction of the smooth muscle.

Using these systems, we found that the cellular concentration of the F-box protein Skp2 is upregulated by increased mechanical tension. Skp2 is the substrate recognition subunit and limiting component of a SKP1–CUL1–F-box ubiquitin ligase complex that promotes proliferation primarily by targeting the cyclin-dependent kinase inhibitor $p27^{KIP1}$ for ubiquitination and, consequently, proteasomal degradation (7, 40, 44). Notably, whereas growth factors regulate Skp2 at the level of protein stability (8), we found that increased mechanical tension upregulates Skp2 expression at the level of transcription. Therefore, Skp2 expression is a point of convergence for signals from mechanical tension and growth factors in the regulation of proliferation.

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We next found that a consensus NFAT-binding site mediates the effects of mechanical tension on the activity of the Skp2 promoter. NFAT is a family of transcription factors that has four members that are activated by increased cytosolic calcium, designated NFATc1 (also known as NFATc or NFAT2), NFATc2 (also known as NFATp or NFAT1), NFATc3 (also known as NFAT4 or NFATx), and NFATc4 (also known as NFAT3) (12, 20). The calcium activates the phosphatase calcineurin through a calmodulin-dependent mechanism (3, 20). By dephosphorylating several serines in NFAT, calcineurin induces a conformational change in NFAT that exposes its nuclear localization signal and conceals its nuclear export signal, which results in its nuclear import (activation) (3, 20).

We found that NFATc1 is activated by increased mechanical tension and that the activation of NFATc1 is necessary for upregulation of Skp2 transcription that occurs in response to increased mechanical tension. Therefore, NFATc1 has a critical role in the mechanoregulation of proliferation. This is a notable finding because, whereas it is well established that cytosolic calcium increases when cells develop mechanical tension and that the increase in calcium promotes proliferation, the pathway(s) that mediates the effect of calcium on proliferation had not been defined. Therefore, we identified the first direct link between calcium signaling and the regulation of the central cell cycle machinery.

MATERIALS AND METHODS

Cell culture and transfections. Bladder smooth muscle cells (SMC; Cambrex) were cultured in SmGM2-medium (Cambrex), aortic SMC (Cell Applications, San Diego, CA) were cultured in SMC growth medium (Cell Applications), and foreskin fibroblasts were cultured in Dulbecco modified Eagle medium with 10% fetal bovine serum (FBS). To construct Skp2-luc, a 423-bp fragment corresponding to sequence from the 5′ flanking region of the human Skp2 gene (GenBank accession no. NT006576) was inserted between the MluI and BglII sites in the pGL3 promoter (Promega). SMC (~80% confluence on 100-mm tissue culture plates) were transfected with 4 μg of the indicated constructs by using Fugene6 (Roche) according to the manufacturer's protocol.

Collagen matrix assays. Cells were suspended in 1.4 mg of collagen (Vitrogen; Cohesion Technologies)/ml, and then the collagen was polymerized according to the manufacturer's protocol. Once the cells developed a spindlelike morphology (~6 h), the collagen matrices were either released from or left fixed to the tissue culture plate, and the cells were used in the assays described below.

Actin staining. SMC were cultured in collagen matrices for 24 h, rinsed with phosphate-buffered saline (PBS), fixed in 4% paraformaldehyde for 10 min, permeabilized with 0.1% Triton X-100 for 5 min, rinsed with PBS, and incubated with Alexa Fluor 488-phalloidin (Molecular Probes) for 20 min. After a rinse with PBS, the cells were visualized by fluorescence microscopy.

BrdU staining. SMC that were cultured in collagen matrices for 24 h were incubated in medium containing 30 μM bromodeoxyuridine (BrdU; Sigma) for an additional 4 h. Cells were isolated from the collagen matrices by incubation in 5 mg of type XI collagenase (Sigma)/ml and analyzed for BrdU uptake by immunofluorescence.

Bladder outlet obstruction. To create a complete bladder outlet obstruction, the urethras of 8- to 10-week-old anesthetized mice were ligated by using a 4-0 silk suture. Partial bladder outlet obstruction was created by placing a 22-gauge catheter alongside the urethra, tying a 4-0 silk ligature firmly around the urethra and the catheter, and then removing the catheter. At the indicated time points, bladders were excised and snap-frozen in liquid nitrogen or fixed in formalin and stained with hematoxylin and eosin.

Immunoblotting. SMC were isolated from the collagen matrices by incubation in 5 mg of type XI collagenase (Sigma)/ml and lysed in Triton buffer (0.5% Triton, 10 mM Tris [pH 8.6], 140 mM NaCl, 1.5 mM $MgCl_2$). Cells cultured on tissue culture plates were pelleted and lysed in sodium dodecyl sulfate (SDS) lysis buffer. Murine bladder smooth muscle tissue was snap-frozen, ground to powder, and lysed in SDS lysis buffer. To obtain nuclear lysate from murine bladder smooth muscle tissue, the tissue was excised and chopped into small pieces and then Dounce homogenized in ice-cold homogenization buffer (50 mM Tris-HCl [pH 7.5], 1.5 mM $MgCl_2$, 2 mM β-mercaptoethanol, 200 mM sucrose, 0.1% Triton X-100). To obtain nuclear lysate from cultured SMC, cells were scraped and incubated in homogenization buffer. The nuclei were pelleted, washed in homogenization buffer without Triton, and repelleted. The isolated nuclei were then lysed in SDS lysis buffer. Complete protease inhibitor cocktail (1×; Roche) and phosphatase inhibitor cocktails (Sigma) were present during the complete procedure. For dephosphorylation of NFATc1, human SMC were harvested in 1× passive lysis buffer (Promega) lacking phosphatase inhibitors, and then the lysate was incubated in 1× phosphatase buffer (Invitrogen) in either the presence or the absence of 1 U of calf intestinal alkaline phosphatase (Invitrogen)/μg at 37°C for 1 h. The following antibodies were used: Skp2 (catalog no. 51-1900) and Skp2 (catalog no. 32-3300) from Zymed; $p27^{KIP1}$ (c-19), $p21^{CIP1}$ (c-19), PCNA (PC10), β-tubulin (H-235), lamin A/C (N-18), and NFATc3 (F-1) from Santa Cruz; NFATc1 (7A6) from BD Pharmingen; and Erk (catalog no. 9102) and phospho-Erk (catalog no. 9106) from Cell Signaling.

RT-PCR. RNA was isolated from the cells in the collagen matrices by using TRIzol (Invitrogen) or from cells growing on tissue culture plates and mouse bladder smooth muscle layer using RNeasy (Qiagen). Reverse transcription-PCR (RT-PCR) was performed using RETROscript (Ambion) and PuReTaq Ready-To-Go PCR beads (GE Healthcare) with the following primers: Skp2 sense, 5′-ATGGGATTCCAGCAAGACTTCTGAA-3′; Skp2 antisense, 5′-GCTCAG GGAGGCACAGACAGGA-3′; $p27^{KIP1}$ sense, 5′-AGCCTGGAGCGGATGG AC-3′; $p27^{KIP1}$ antisense, 5′-CTTGGGCGTCTGCTCCACA-3′; b-myb sense, 5′-GATGTGCCGGAGCAGAGGGATAG-3′; b-myb antisense, 5′-GTCCATG GCCCCTTGACAAGGTC-3′; β-actin sense, 5′-GTGATGGTGGGCATGGGT CA-3′; β-actin antisense, 5′-TTAATGTCACGCACGATTTCCC-3′; GAPDH sense, 5′-GGTGAAGGTCGGAGTCAACG-3′; and GAPDH antisense, 5′-CA AAGTTGTCATGGATGACC-3′.

Luciferase assays. Luciferase assays were performed by using a luciferase assay system (Promega). Immunoblots for β-tubulin were performed to confirm that equal numbers of cells were assayed (data not shown).

Actinomycin D treatment. Human SMC were seeded in collagen matrices as described above. Approximately 6 h after the collagen had polymerized, the media was changed to SmGM-2 containing 1 μg of actinomycin D (Sigma)/ml, and the collagen matrices were either released from or left fixed to the tissue culture plate. At the indicated time points, RNA was isolated for RT-PCR analysis.

siRNA transfection. Small interfering RNAs (siRNAs) were transfected by using GeneEraser reagent (Stratagene) according to the manufacturer's protocol. The following siRNA sequences were used: scrambled sense, 5′-AUGUAU UGGCCUGUAUUAGUU-3′; scrambled antisense, 5′-CUAAUACAGGCCA AUACAUUU-3′; Skp2(A) sense, 5′-AAGGGAGUGACAAAGACUUUG-3′; Skp2(A) antisense, 5′-CAAAGUCUUUGUCACUCCCUU-3′; Skp2(B) sense, 5′-AAUCUAAGCCUGGAAGGCCUG-3′; Skp2(B) antisense, 5′-CAGGCCU UCCAGGCUUAGAUU-3′; NFATc1(A) sense, 5′-CGUAUGAGCUUCGGA UUGAUU-3′; NFATc1(A) antisense, 5′-UCAAUCCGAAGCUCAUACGUU-3′; NFATc1(B) sense, 5′-GAAACUCCGACAUUGAACUTT-3′; and NFATc1(B) antisense, 5′-TTAGUUCAAUGUCGGAGUUUC-3′. Cells were transfected twice at an interval of 24 h with Skp2 siRNAs and at an interval of 36 h with NFATc1 siRNAs.

ChIP assay. Mouse bladder smooth muscle tissue was chopped into small pieces, cross-linked with 1% formaldehyde in 1× PBS, and sonicated. Samples were processed according to the chromatin immunoprecipitation (ChIP) kit manufacturer's protocols (Upstate). DNA was recovered by using the phenol-chloroform method. The immunoprecipitated DNA was subjected to PCR assays with the following primer pairs: Skp2 promoter sense, 5′-CGTCTGGAAGGG ACTCAGAAG-3′; Skp2 promoter antisense, 5′-AACCCTCCAGATACCCAC AA-3′; β-globin sense, 5′-CCTGCCCTCTCTATCCTGTG-3′; and β-globin sense, 5′-GCAAATGTGTTGCCAAAAAG-3′. The NFATc1 antibody (H-110) was from Santa Cruz.

RESULTS

The development of mechanical tension is critical for smooth muscle proliferation. We initiated our studies by using a tissue culture system in which the effects of mechanical tension on cells such as SMC and fibroblasts can be assessed (4, 16, 17). Importantly, SMC and fibroblasts attempt to contract as they spread. If they are plated on a rigid substrate, such as a tissue culture dish, they develop mechanical tension as they

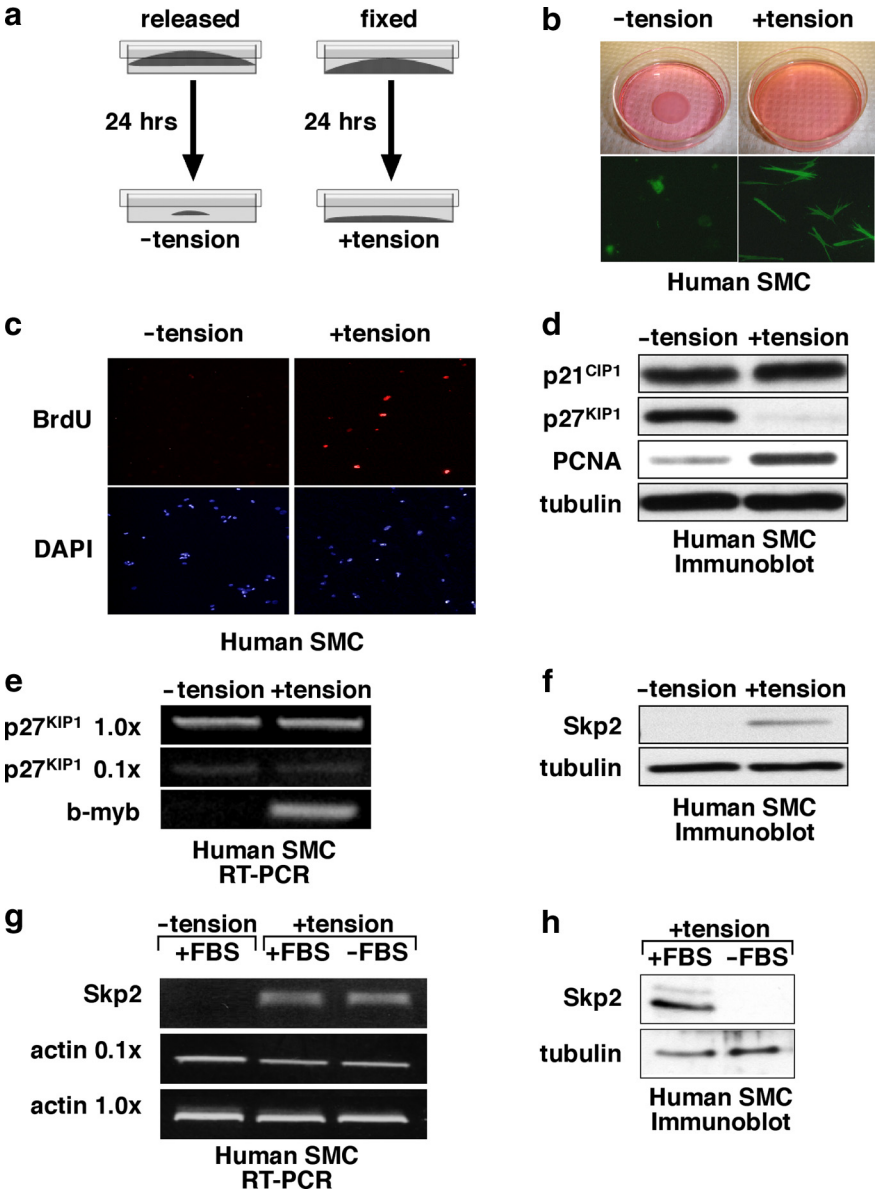

FIG. 1. Mechanoregulation of smooth muscle proliferative signals in a tissue culture model. (a) Schematic of a tissue culture system to study the effects of mechanical tension on proliferation (see text for details). (b) Fluorescence staining with Alexa Fluor 488-phalloidin for actin in human bladder SMC in released (–tension) and fixed (+tension) collagen matrices. (c) BrdU and DAPI (4′,6′-diamidino-2-phenylindole) staining of human bladder SMC isolated from released (–tension) and fixed (+tension) collagen matrices. (d) Immunoblots of $p21^{CIP1}$, $p27^{KIP1}$, PCNA, and β-tubulin in human bladder SMC isolated from released (–tension) and fixed (+tension) collagen matrices. (e) RT-PCR for $p27^{KIP1}$ and b-myb mRNA in human bladder SMC isolated from released (–tension) and fixed (+tension) collagen matrices (two different concentrations of the RT reaction products were loaded to confirm that the $p27^{KIP1}$ PCR was in the linear range). The level of b-myb mRNA was used as a proliferative marker. (f) Immunoblots of Skp2 and β-tubulin in human bladder SMC isolated from released (–tension) and fixed (+tension) collagen matrices. (g) RT-PCR for Skp2 and actin mRNA in human bladder SMC isolated from collagen matrices that were either released from (–tension) or left fixed to (+tension) the tissue culture dish in either serum-containing (+FBS) or serum-free (–FBS) media (two different concentrations of the RT reaction products were loaded to confirm that the actin PCR was in the linear range). (h) Immunoblots of Skp2 and β-tubulin in human bladder SMC isolated from collagen matrices that were left fixed to (+tension) the tissue culture dish in either serum-containing (+FBS) or serum-free (–FBS) medium.

attempt to contract against the resistance of the substrate (6, 13). The development of mechanical tension by the cells is necessary for proliferation to occur (6, 13). In the tissue culture model we used, cells are seeded in three-dimensional collagen matrices, and then each matrix is either released from the tissue culture dish and allowed to float freely in the medium or left fixed to the dish (Fig. 1a). The released matrices offer little resistance to the contraction of the cells; hence, only a relatively low level of mechanical tension develops within the cells. In contrast, the fixed matrices resist contraction, which allows for the development of an elevated level of mechanical tension within the cells (16). The difference in mechanical tension

within the released and fixed matrices is demonstrated by the finding that whereas stress fibers fail to develop in SMC in the released matrices, they form in cells in the fixed matrices (Fig. 1b). Thus, the released and fixed collagen matrices simulate the mechanical environments of nonstressed tissue and tissue in which the mechanical tension is increased, respectively. Importantly, whereas SMC in the released matrices do not proliferate, those in the fixed matrices do (few if any of the cells in a released matrix take up BrdU, while ca. 40% of the cells in a fixed matrix take up BrdU under the conditions of our assay) (Fig. 1c), indicating that the proliferation of the cells is regulated by mechanical tension in this system.

Skp2 is a node at which proliferative signals from soluble growth factors and mechanical tension are integrated in the regulation of proliferation in isolated SMC. To begin to understand the mechanism by which proliferative signals regulated by mechanical tension are coupled to the central cell cycle machinery, we first examined the effect of increased mechanical tension in SMC on the expression of two cyclin-dependent kinase inhibitors that have been implicated in the regulation of smooth muscle proliferation (42). We found that whereas the level of $p21^{CIP1}$ in the cells is unaffected by increased mechanical tension, the level of $p27^{KIP1}$ falls dramatically when mechanical tension is increased (Fig. 1d). The decrease in $p27^{KIP1}$ correlates with an increase in PCNA expression (Fig. 1d). Because $p27^{KIP1}$ serves to inhibit cell cycle progression (34), these findings suggested that $p27^{KIP1}$ has a role in the mechanoregulation of proliferation.

We therefore began to examine the mechanism by which smooth muscle $p27^{KIP1}$ is downregulated by increased mechanical tension. We found that changes in mechanical tension have no effect on the level of $p27^{KIP1}$ mRNA (Fig. 1e). It had previously been found that growth factors have no effect on $p27^{KIP1}$ mRNA levels; instead, growth factors downregulate $p27^{KIP1}$ by inducing its degradation (31). Therefore, we hypothesized that increased mechanical tension also downregulates $p27^{KIP1}$ by inducing its degradation.

The degradation of $p27^{KIP1}$ that occurs upon growth factor stimulation is mediated by the upregulation of expression of Skp2, a component of a ubiquitin ligase complex that targets $p27^{KIP1}$ for ubiquitination, and, consequently, proteasome-mediated degradation (7, 29, 40). Therefore, we examined the effect of increased mechanical tension on Skp2. We found that increased mechanical tension induces an increase in Skp2 (Fig. 1f), which suggested that the proliferative response that occurs in response to increased mechanical tension is mediated in part by Skp2.

To examine the mechanism by which an increase in mechanical tension increases the level of Skp2, we assessed the effect of mechanical tension on Skp2 mRNA. Growth factors increase Skp2 levels by stabilizing Skp2 protein (8, 48); in contrast, we found that the development of mechanical tension induces an increase in Skp2 mRNA (Fig. 1g). The increase of Skp2 mRNA in response to increased mechanical tension is growth factor independent, as indicated by the finding that the level of Skp2 mRNA is unaffected by serum deprivation (Fig. 1g). Serum deprivation, however, downregulates SMC Skp2 protein levels (Fig. 1 h). Therefore, whereas growth factors regulate Skp2 at the protein level, mechanical tension regulates Skp2 at the mRNA level. Hence, Skp2 expression is a point of convergence at which signaling from growth factors and mechanical tension are integrated.

Skp2 is a node at which proliferative signals from soluble growth factors and mechanical tension are integrated in the regulation of proliferation in intact smooth muscle tissue. We next wanted to confirm that these findings are relevant to the mechanoregulation of proliferation in intact smooth muscle tissue. The rodent urinary bladder is an ideal system for studies of the smooth muscle response to changes in mechanical tension for several reasons. (i) The mechanical tension in the bladder smooth muscle layer can readily be increased by obstructing the bladder outlet—the increase is due to smooth muscle contraction against the increased resistance to urine flow caused by the obstruction. (ii) The SMC in the rodent bladder proliferate in response to the increase in mechanical tension that develops when there is a bladder outlet obstruction (18, 24, 37, 45). (iii) The smooth muscle layer of the bladder is one of the thickest smooth muscle layers in the body. Therefore, it can serve as a source of a relatively large amount of smooth muscle tissue for detailed study (immunoblotting, RNA studies, etc.). (iv) The mechanical environment within the wall of an obstructed bladder can be simulated in tissue culture by allowing bladder SMC to contract against a semirigid support—as in the tissue culture system described above. This allows for the study of mechanical tension as an independent factor and it facilitates further analyses of findings that arise from studies performed on the intact bladder smooth muscle layer.

Strikingly, when we examined the effects of bladder outlet obstruction on the smooth muscle layer, our findings were precisely the same as the findings derived from isolated cells in the model described above. The increased tension in the bladder wall that develops when there is an obstruction has no effect on the level of $p21^{CIP1}$ in the smooth muscle, but it induces a decrease in the level of $p27^{KIP1}$ that correlates with an increase in PCNA (Fig. 2a). In addition, despite the fall in the level of $p27^{KIP1}$ protein, the level of the $p27^{KIP1}$ mRNA remains unchanged when there is an obstruction (Fig. 2b). Furthermore, the concentration of Skp2 protein is upregulated when there is an obstruction (Fig. 2c). Finally, the upregulation of Skp2 is mediated at least in part by an upregulation of Skp2 mRNA (Fig. 2d). These findings serve to validate our tissue culture system as an appropriate model for the study of the effects of mechanical tension on proliferation in intact smooth muscle tissue and, more importantly, when considered along with the findings from the tissue culture system, they strongly suggest that Skp2 is regulated at the mRNA level by changes in mechanical tension in intact smooth muscle.

We next wanted to confirm that Skp2 is truly important in the proliferative response to increased mechanical tension. We first used two different siRNAs to inhibit Skp2 expression in human bladder SMC. Inhibition of Skp2 expression increased the level of $p27^{KIP1}$ protein (Fig. 3a) and decreased proliferation (Fig. 3b). We then compared the effect of a partial bladder outlet obstruction in wild-type and $skp2^{-/-}$ mice (28) after 14 days. As expected based on previous studies of bladder outlet obstruction (18, 24, 37, 45), we found an extensive hyperplastic response in the bladder smooth muscle layer of the wild-type ($skp2^{+/+}$) mice (Fig. 3c). In contrast, however, we found that even though there is gross hypertrophy of the bladder smooth

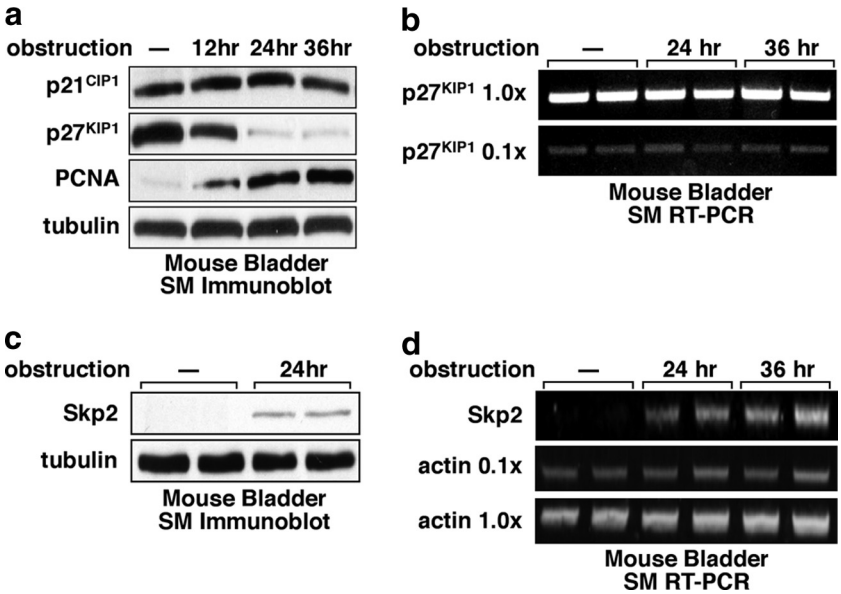

FIG. 2. Mechanoregulation of smooth muscle proliferative signals in intact tissue. (a) Immunoblots of $p21^{CIP1}$, $p27^{KIP1}$, PCNA, and β-tubulin in the smooth muscle layer of mouse bladders that were either unobstructed or completely obstructed for the time indicated (each lane in this and subsequent bladder obstruction experiments represents an assessment of the protein or RNA from an individual mouse). (b) RT-PCR for $p27^{KIP1}$ mRNA in the smooth muscle layer of mouse bladders that were either unobstructed or completely obstructed for the time indicated (two different concentrations of the RT reaction products were loaded to confirm that the $p27^{KIP1}$ PCR was in the linear range). (c) Immunoblots of Skp2 and β-tubulin in the smooth muscle layer of mouse bladders that were either unobstructed or completely obstructed for the time indicated. (d) RT-PCR for Skp2 and actin mRNA in the smooth muscle layer of mouse bladders that were either unobstructed or completely obstructed for the time indicated (two different concentrations of the RT reaction products were loaded to confirm that the actin PCR was in the linear range).

muscle layer in response to a bladder outlet obstruction in *skp2*$^{-/-}$ mice (Fig. 3c), the hyperplastic response is markedly decreased in the *skp2*$^{-/-}$ mice, as indicated by the relative paucity of nuclei in the bladder smooth muscle of *skp2*$^{-/-}$ mice (Fig. 3c). The decreased bladder smooth muscle hyperplastic response seems to be compensated for by increased cellular hypertrophy, as evidenced by the visibly increased thickness of the smooth muscle bundles in the obstructed bladders of *skp2*$^{-/-}$ mice (Fig. 3c). These were not surprising findings because they are consistent with the finding that hepatocytes increase in size but not number during liver regeneration after partial hepatectomy in *skp2*$^{-/-}$ mice (27) (which is in contrast to wild-type mice in which liver regeneration is primarily a proliferative response). In addition, in a manner analogous to the hypertrophy of the bladder wall that occurs in response to obstruction in the *skp2*$^{-/-}$ mice, the volume and mass of the livers of *skp2*$^{-/-}$ mice are completely restored after partial hepatectomy despite the lack of a hepatocyte proliferative response (27). Also consistent with our findings is the finding that there is a marked increase in the number of proliferating renal tubular cells in a murine model of unilateral ureteral obstruction in wild-type mice, but there is no change in the number of proliferating renal tubular cells in response to a ureteral obstruction in *skp2*$^{-/-}$ mice (41). Our results identify Skp2 as a critical mediator of the proliferative response that occurs in the bladder smooth muscle layer when there is bladder outlet obstruction—they therefore demonstrate the importance of mechanoregulation of Skp2 mRNA levels in the SMC hyperplastic response to increased tissue tension.

Mechanical tension regulates Skp2 mRNA levels in several types of cells. We next wanted to determine whether the regulation of Skp2 mRNA by mechanical tension is a generalized phenomenon that occurs in other tissues. Smooth muscle proliferation during vascular development and remodeling is regulated in part by localized mechanical forces within the vascular wall (21). Similarly, mechanical tension is thought to be important in the regulation of fibroblast proliferation during both tissue repair and pathological fibroproliferative responses (16, 21). Therefore, it is notable that, using the collagen matrix system described above, we found that Skp2 mRNA is upregulated by mechanical tension in primary human vascular SMC, primary human dermal fibroblasts (Fig. 4), and primary human lung fibroblasts (data not shown). The finding that Skp2 mRNA is regulated by mechanical tension in SMC and fibroblasts suggests that the regulation of Skp2 mRNA by changes in mechanical tension is a component of many, if not all, physiologic and pathological processes in which mechanical tension regulates proliferation.

A consensus binding site for the transcription factor NFAT has a critical role in the mechanoregulation Skp2 promoter activity. We next sought to determine the mechanism by which mechanical tension regulates Skp2 mRNA levels. Two independent findings initially suggested that mechanical tension regulates Skp2 at the transcriptional level: we found that (i) the stability of Skp2 mRNA is unaltered by changes in mechanical tension (Fig. 5a) and (ii) the activity of a reporter construct driven by a 423-bp sequence from the 5′-flanking region of the Skp2 gene (Skp2-luc) is increased in SMC in a fixed collagen matrix compared to its activity in a released matrix (Fig. 5b).

We next found that a consensus binding site for the calcium-regulated transcription factor NFAT has a role in mediating the effects of mechanical tension on the activity of the Skp2

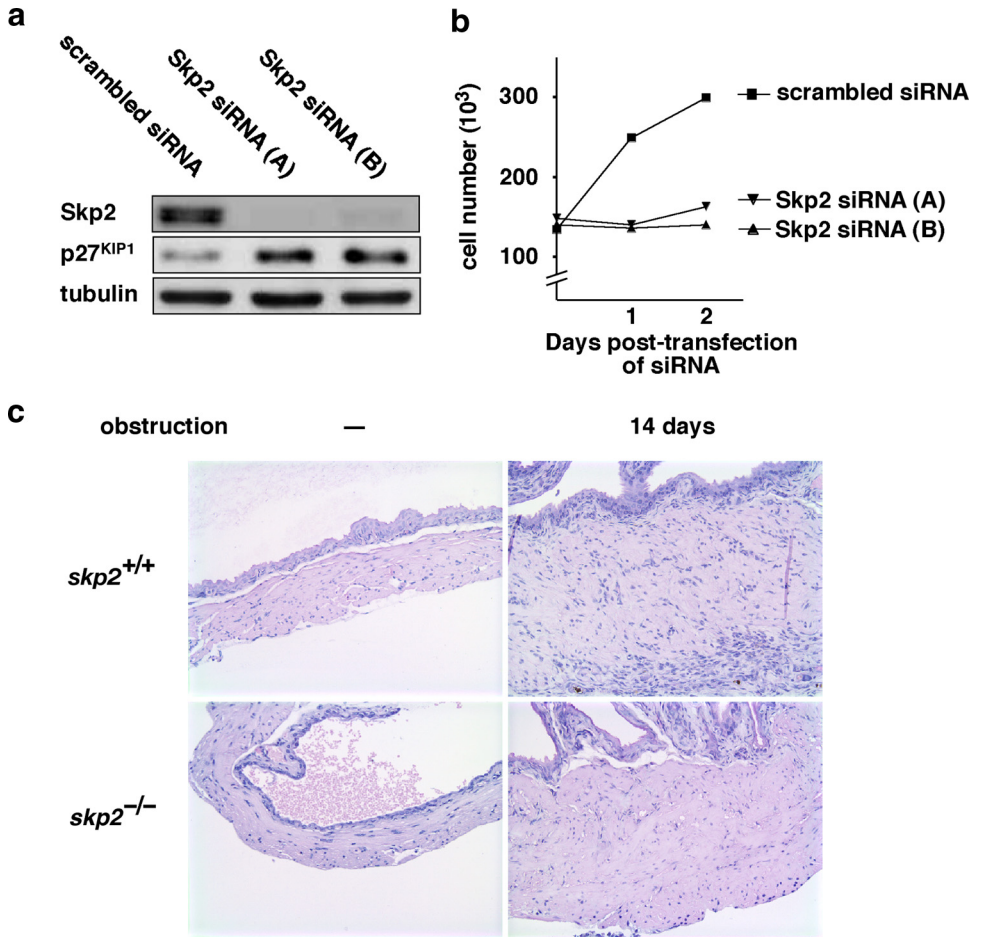

FIG. 3. Skp2 is required for bladder smooth muscle proliferation both in tissue culture and in intact tissue. (a) Immunoblots for Skp2, $p27^{KIP1}$, and tubulin in human bladder SMC that were adherent to a tissue culture dish and transfected with scrambled or two different Skp2-specific siRNAs. (b) Cell numbers at indicated time points of human SMC that were adherent to a tissue culture dish and transfected as in panel a. (c) The bladder walls of $skp2^{+/+}$ and $skp2^{-/-}$ mice that were either unobstructed or partially obstructed for 14 days and then fixed and stained with hematoxylin and eosin.

promoter: (i) its deletion abolishes the tension responsiveness of the Skp2 promoter in SMC (Fig. 5b) and (ii) its addition to a nonresponsive minimal promoter imparts tension responsiveness to the promoter in SMC (Fig. 5c). We therefore sought to determine whether NFAT activity increases in response to increased mechanical tension in an intact smooth muscle layer.

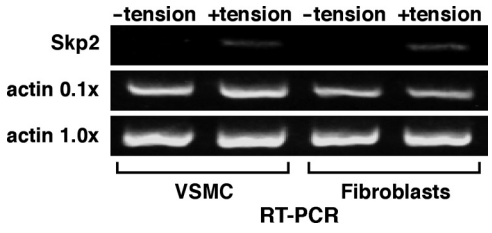

FIG. 4. Skp2 mRNA expression is regulated by mechanical tension in human vascular SMC and human fibroblasts. RT-PCR for Skp2 and actin mRNA in human vascular SMC and in human foreskin fibroblasts isolated from released (–tension) and fixed (+tension) collagen matrices (two different concentrations of the RT reaction products were loaded to confirm that the actin PCR was in the linear range).

To examine this, we assessed the effect of a bladder outlet obstruction on NFAT activity in the bladder smooth muscle layer of mice that are transgenic for an NFAT-responsive luciferase reporter construct (kindly provided by Benjamin Wilkins and Jeffery Molkentin) (46). This reporter is driven by NFAT-binding sites such that luciferase is expressed when an NFAT family member is activated in the tissue under study. We found that luciferase activity in the bladder smooth muscle layer increased three- to fourfold in response to bladder outlet obstruction in these mice (Fig. 5d). In addition, it had previously been demonstrated that an NFAT-dependent target, cyclooxygenase-2, is upregulated at the mRNA level by increased mechanical tension in isolated bladder SMC and in response to a bladder outlet obstruction in the bladder smooth muscle layer (22, 32). Together, these findings provided evidence that an NFAT family member(s) has a role in the upregulation of Skp2 transcription that occurs when mechanical tension is increased in smooth muscle tissue.

Notably, the NFAT site is conserved in the human and mouse Skp2 promoters (Fig. 6a) and its sequence is an exact match with the NFAT-binding site in the human interleukin-2

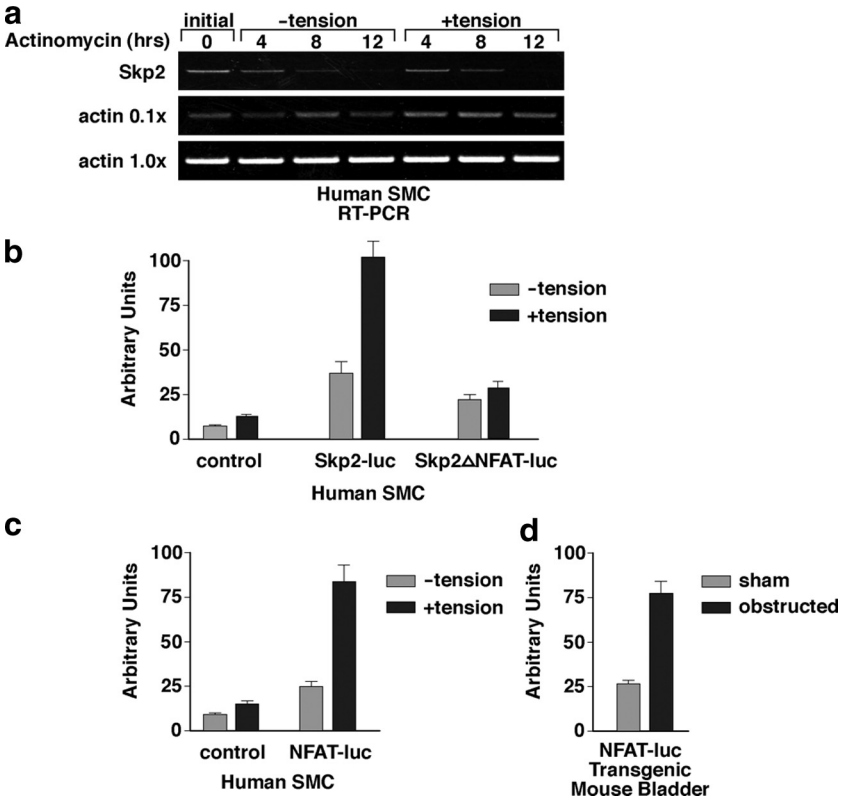

FIG. 5. A consensus NFAT-binding sequence mediates the mechanoregulation of Skp2 transcription, and NFAT activity is increased by increased mechanical tension in intact tissue. (a) Human bladder SMC were first allowed to develop tension in collagen matrices. The cells were then treated with actinomycin D and the matrices were either released from (–tension) or left fixed to (+tension) the tissue culture dish ("0 h"). Cells were harvested to perform RT-PCR for Skp2 and actin mRNA at the indicated time points (two different concentrations of the RT reaction products were loaded to confirm that the actin PCR was in the linear range). (b) Luciferase assays of human bladder SMC transfected with (i) pGL3-promoter (control), (ii) a construct in which 423 bp of the 5′ flanking region of the Skp2 gene drives a luciferase reporter (Skp2-luc), or (iii) a construct in which a consensus NFAT-binding site (AGGAAAA) (38) has been deleted from Skp2-luc (Skp2ΔNFAT-luc) isolated from collagen matrices that were either released from (–tension) or left fixed to (+tension) the tissue culture dish. (c) Luciferase assay as in panel B, except using human bladder SMC transfected with pGL3-promoter (control) or pGL3-promoter driven by five tandem repeats of the Skp2 NFAT-binding site (NFAT-luc). (d) Luciferase assay using the smooth muscle layer of bladders from mice transgenic for an NFAT-luc reporter that were either unobstructed (sham) or completely obstructed for 24 h (the mean values obtained from three mice for each condition).

(IL-2) promoter, the prototypical NFAT-regulated promoter (38) (Fig. 6a). Furthermore, there is extensive conservation between the surrounding sequence of the NFAT site in the human and mouse Skp2 promoters and the IL-2 NFAT site in that the region 5′ to each of the sites is GA rich and the sequence NCNG is conserved 3′ to the NFAT-binding site in all three promoters (Fig. 6a). These findings provide further evidence that a member(s) of the NFAT family of transcription factors mediates the mechanoregulation of Skp2 transcription.

NFATc1 undergoes dephosphorylation and nuclear translocation in response to increased mechanical tension. NFAT family members are activated when they are dephosphorylated by the phosphatase calcineurin. Upon activation, they are imported into the nucleus where they bind their cognate promoter-binding sites (20). There are four calcineurin-regulated NFAT isoforms, NFATc1 to NFATc4. Their expression varies between different types of smooth muscle (5, 15, 19, 25, 39, 49), and there are instances in which the individual NFAT isoforms are differentially regulated within the same type of SMC (5, 49). Once in the nucleus, the localization of NFAT proteins is regulated by a series of kinases; it is likely that these kinases mediate the differential regulation of the individual NFAT isoforms (19).

We examined the most well-studied smooth muscle NFAT proteins, NFATc1 and NFATc3, in human bladder SMC. It would be difficult to examine NFAT activation using the collagen matrix assay, because tension is relieved as the cells are isolated from the collagen matrix and NFAT proteins are rapidly exported from the nucleus after cessation of the activating signal (43). However, cells develop tension as they spread on the rigid surface of a tissue culture dish (6, 13). Therefore, we initially used adhesion and subsequent spreading as a surrogate for the development of tension in a collagen matrix. We found little or no change in nuclear NFATc3 upon adhesion (Fig. 6b). However, in the same lysates, we found that a rapidly migrating form of NFATc1 develops in the adherent, spread cells that is not present in suspended cells (Fig. 6b). Notably, a comparison of nuclear lysates and whole-cell lysates reveals that relative to the other forms of NFATc1, this form is concentrated in the nucleus (Fig. 6b), which is consistent with dephosphorylation mediating the nuclear localization of NFATc1. Indeed, phosphatase treatment of whole-cell lysates

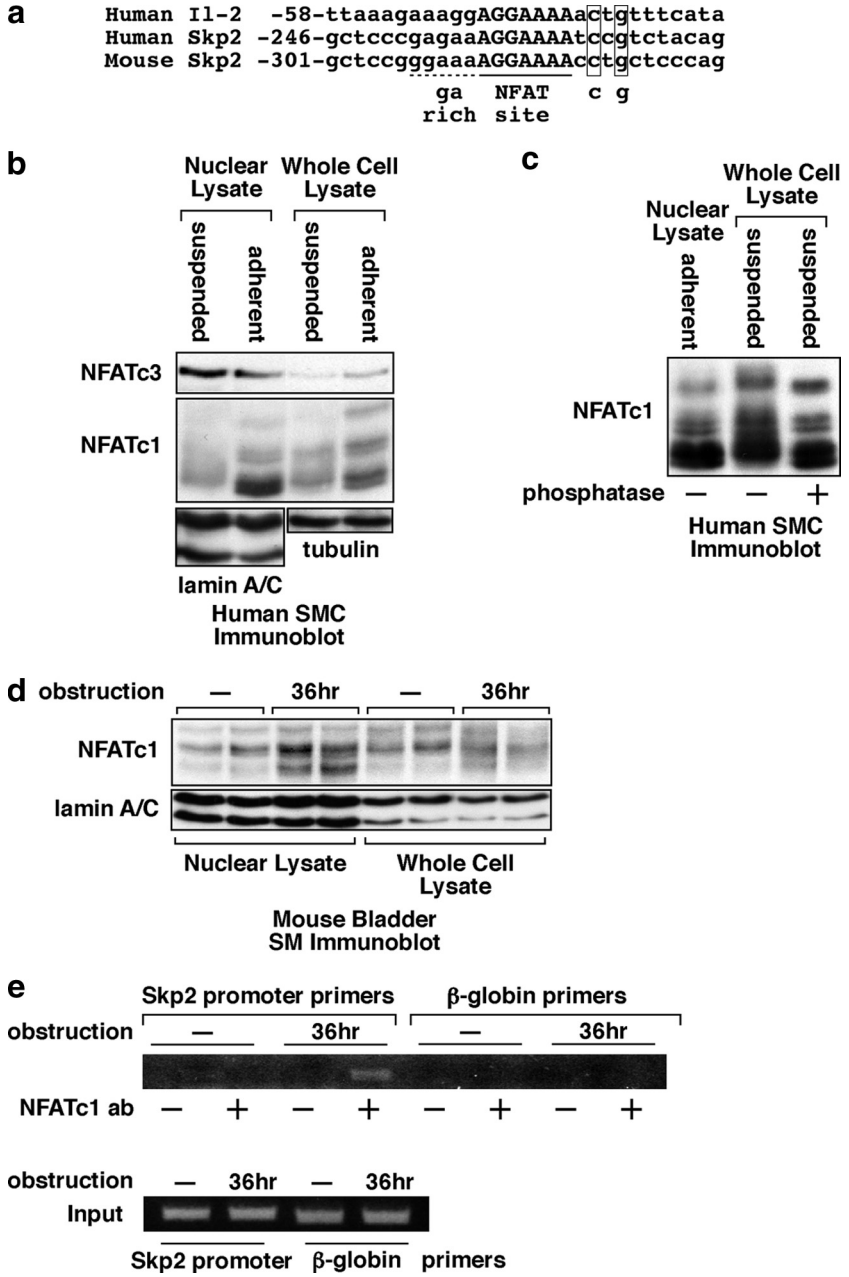

FIG. 6. NFATc1 directly targets the Skp2 promoter. (a) Comparison of the NFAT-binding site and surrounding sequence in the human and mouse Skp2 promoters with the NFAT-binding site and surrounding sequence in the human IL-2 promoter, the prototypical NFAT-binding site (38). (b) Immunoblot of NFATc3 and NFATc1 in nuclear lysates and whole-cell lysates of adherent and suspended human bladder SMC. Lamin A/C and tubulin were used as loading controls. (c) Immunoblot of NFATc1 in whole-cell lysates of suspended human bladder SMC treated with calf intestinal alkaline phosphatase as indicated. Nuclear lysates of adherent cells were used as a reference. (d) Immunoblot for NFATc1 in nuclear lysates and whole-cell lysates from the smooth muscle layer of mouse bladders that were partially obstructed as indicated. Lamin A/C was used as a loading control. (e) ChIP assay of the endogenous Skp2 promoter in the bladder smooth muscle layer of mouse bladders that were either unobstructed or partially obstructed as indicated. Primers targeted to the 5′-untranslated region of the β-globin gene were used as a control for specificity.

of suspended cells results in the formation of an NFATc1 protein that migrates in the same position as this rapidly migrating form (Fig. 6c). Similarly, the nuclear levels of the fastest-migrating form of NFATc1 increases in the bladder smooth muscle layer in response to a bladder outlet obstruction and this form is concentrated in the nucleus (Fig. 6d). Together, these data strongly suggest that increased mechanical tension induces the dephosphorylation and consequent nuclear localization of NFATc1.

NFATc1 is a critical mediator in the regulation of Skp2 transcription by changes in mechanical tension. We next found that NFATc1 binds to the Skp2 promoter in the bladder

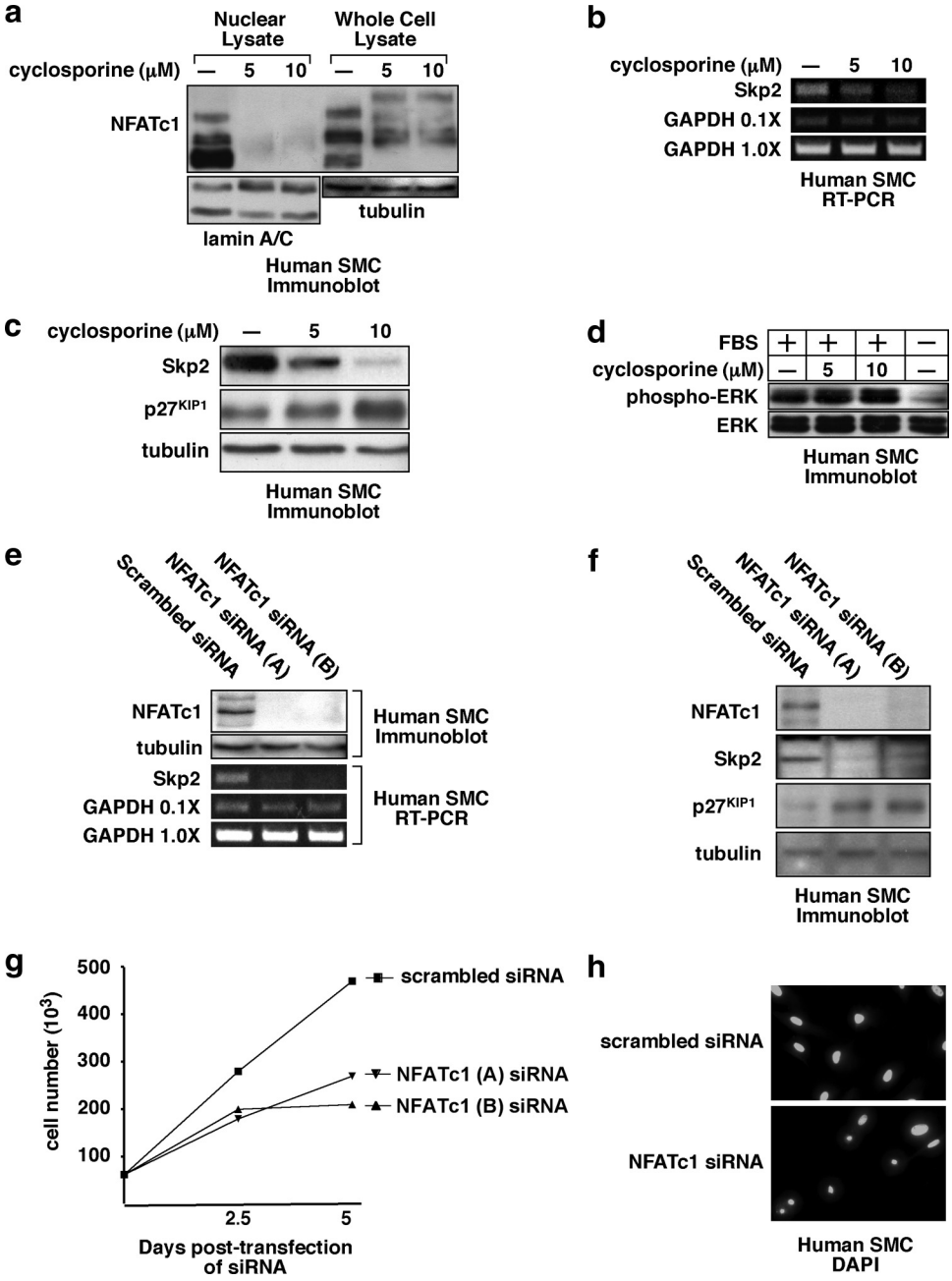

FIG. 7. NFATc1 regulates Skp2 expression. (a) Immunoblot for NFATc1 in human bladder SMC that were adherent to a tissue culture dish and treated with indicated concentrations of cyclosporine for 12 h. (b) RT-PCR for Skp2 and GAPDH mRNA in human bladder SMC that were adherent to a tissue culture dish and treated with cyclosporine as in panel a (two different concentrations of the RT reaction products were loaded to confirm that the GAPDH PCR was in the linear range). (c) Immunoblots for Skp2, $p27^{KIP1}$, and tubulin in human bladder SMC that were adherent to a tissue culture dish and treated with cyclosporine as in panel a. (d) Immunoblots for Erk and phospho-Erk in human bladder SMC that were adherent to a tissue culture dish and treated with cyclosporine as in panel a. Cells grown in the absence of serum (FBS) were used as a positive control for dephosphorylated Erk. (e) Immunoblots for NFATc1 and tubulin and RT-PCR for Skp2 and GAPDH mRNA in human bladder SMC that were adherent to a tissue culture dish and transfected with scrambled or two different NFATc1-specific siRNAs (two different concentrations of the RT reaction products were loaded to confirm that the GAPDH PCR was in the linear range). (f) Immunoblots for NFATc1, Skp2, $p27^{KIP1}$, and tubulin in human bladder SMC that were adherent to a tissue culture dish and then transfected as in panel e. (g) Cell numbers at indicated time points of human SMC that were adherent to a tissue culture dish and transfected as in panel e. (h) DAPI-stained nuclei of human bladder SMC 120 h after the cells were transfected as in panel e. Similar results were obtained with both NFATc1 siRNAs.

smooth muscle layer when there is a bladder outlet obstruction (Fig. 6e), which provided evidence for a role for NFATc1 in mediating the upregulation of Skp2 transcription in response to increased mechanical tension. To further examine whether NFATc1 does indeed have role in the mechanoregulation of Skp2 transcription, we treated bladder SMC with the calcineurin inhibitor cyclosporine and found that it blocks NFATc1 nuclear localization (Fig. 7a) and inhibits Skp2

mRNA expression (Fig. 7b) and Skp2 protein expression (Fig. 7c). Importantly, the effect of cyclosporine treatment on Skp2 mRNA is not due to a generalized effect on proliferative signals, since cyclosporine treatment does not inhibit ERK phosphorylation at concentrations that block NFATc1 activity (Fig. 7d). Strikingly, these findings are consistent with a recent report that systemically administered cyclosporine inhibits the bladder smooth muscle response to obstruction in a rabbit model of bladder outlet obstruction (10).

To confirm that NFATc1 has a role in the regulation of Skp2 expression in SMC, we used siRNA to inhibit NFATc1 expression. Inhibition of NFATc1 protein expression decreased Skp2 mRNA (Fig. 7e) and Skp2 protein (Fig. 7f) and increased $p27^{KIP1}$ protein (Fig. 7f), confirming a role for NFATc1 in the mechanoregulation of Skp2 transcription and proliferative signaling downstream of Skp2. Interestingly, although NFATc1 siRNA blocks cellular proliferation (Fig. 7g), a component of the block is due to cell death since we found that inhibition of NFATc1 expression ultimately caused nuclear condensation (Fig. 7 h), which is consistent with the previous findings that NFAT inhibition results in cardiomyocyte apoptosis (35) and that a constitutively active form of NFATc1 is antiapoptotic in fibroblasts (30). Therefore, NFATc1 activates both proliferative and survival signals in the mechanoregulation of proliferation.

DISCUSSION

We have demonstrated that signaling from mechanical tension upregulates Skp2 transcription. It has previously been shown that adhesion is necessary to support Skp2 transcription (8). We have added a critical refinement to this finding by demonstrating that adhesion per se, while necessary, is not sufficient for the upregulation of Skp2 transcription; we found that even when a cell is adherent to collagen, it must develop and maintain mechanical tension to support transcription of Skp2. Indeed, we found that the changes in NFATc1 that occur when isolated bladder SMC adhere to a tissue culture dish (Fig. 5b) are similar to the changes in NFATc1 that occur in the bladder smooth muscle layer in response to the increase in bladder wall tension that occurs when there is a bladder outlet obstruction (Fig. 5d) and that the changes are due to dephosphorylation (Fig. 5c), suggesting that the changes in NFATc1 that occur upon adhesion are due to the development of mechanical tension once the adherent cell spreads. Further supporting this argument is the finding that the level of Skp2 mRNA in adherent cells can be regulated by changes in cell shape (26). By examining NFATc1 activation and Skp2 mRNA expression in intact tissue, we have demonstrated the importance of the distinction between adhesion per se and the development of mechanical tension by an adherent cell.

Smooth muscle contraction is initiated by an increase in sarcoplasmic calcium. Calcium binds and thereby activates calmodulin, which in turn activates calmodulin-dependent myosin light-chain kinase. By catalyzing myosin phosphorylation, calmodulin-dependent myosin light-chain kinase activates actin-myosin cross-bridge cycling, causing mechanical force to be generated (1). Calcium/calmodulin signaling is also essential for cell cycle progression; however, the downstream effectors that mediate the calcium/calmodulin proliferative signals have not previously been identified (23). One proximal target of calcium/calmodulin signaling is the phosphatase calcineurin and it has been established that the activation of calcineurin is critical for the proliferative effects of increased calcium (23). This is notable because when calcineurin is activated, it dephosphorylates NFAT, and thereby induces its nuclear translocation. Therefore, our finding that NFATc1 mediates the mechanoregulation of Skp2 transcription identifies NFATc1 as a direct link between the proliferative signals mediated by the calcium/calmodulin/calcineurin pathway and the central cell cycle machinery. Our findings therefore in part explain the role of calcium in proliferation.

The E2F family of transcription factors has a central role in the regulation of proliferation (33). Hence, it is notable that E2F has a role in the transcriptional activation of Skp2 in mouse embryo fibroblasts (50) and in tumor cells that express high levels of E2F (51). However, it has been shown that E2F is not important for the transcriptional activation of Skp2 in tumor cells that only express low levels of E2F or in human foreskin fibroblasts (51). This is notable because we found that serum starvation has no effect on Skp2 mRNA levels in human bladder SMC (Fig. 1g) and the Pagano and Krek laboratories found that serum starvation has no effect on Skp2 mRNA levels in human diploid fibroblasts (8, 48). Because serum starvation induces the pocket proteins to bind to and inactivate E2F proteins (11), these findings imply that E2F does not have a significant role in the transcriptional activation of Skp2 in human SMC and human diploid fibroblasts and our finding specifically implies that E2F does not have a role in the mechanoregulation of Skp2 transcription in human bladder SMC. It is important to note, however, that E2F may have a role in the mechanoregulation of Skp2 transcription in other cell types.

Finally, our finding that Skp2 is regulated by mechanical tension at the mRNA level in vascular smooth muscle and fibroblasts, in addition to bladder smooth muscle, suggests that the regulation of Skp2 transcription by changes in mechanical tension is a component of many, if not all, physiologic and pathological processes in which mechanical tension regulates cellular proliferation. Intriguingly, calcineurin-mediated NFATc1 activation has a critical role in cardiac valve and outflow tract development (9, 14, 36), as well as osteoblast proliferation during skeletal development and repair (47). These are processes in which the mechanoregulation of proliferation is likely to have a critical role. It is possible that Skp2 is an NFATc1 target in each of these.

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