The RNA-Binding Protein KSRP Promotes Decay of β-Catenin mRNA and Is Inactivated by PI3K-AKT Signaling

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β-catenin plays an essential role in several biological events including cell fate determination, cell proliferation, and transformation. Here we report that β-catenin is encoded by a labile transcript whose half-life is prolonged by Wnt and phosphatidylinositol 3-kinase–AKT signaling. AKT phosphorylates the mRNA decay-promoting factor KSRP at a unique serine residue, induces its association with the multifunctional protein 14-3-3, and prevents KSRP interaction with the exoribonucleolytic complex exosome. This impairs KSRP’s ability to promote rapid mRNA decay. Our results uncover an unanticipated level of control of β-catenin expression pointing to KSRP as a required factor to ensure rapid degradation of β-catenin in unstimulated cells. We propose KSRP phosphorylation as a link between phosphatidylinositol 3-kinase–AKT signaling and β-catenin accumulation.


Introduction

The half-life (t½) of mRNAs is regulated in a complex fashion in response to external stimuli. Whereas transcripts containing the AU-rich element (ARE) are labile, activation of signal transduction pathways induces their stabilization [1]. It is now clear that mRNA decay regulation by different signals makes a huge contribution to the global control of gene expression [1]. AREs, located in the 3’ untranslated region (3’ UTR) of many short-lived transcripts, promote mRNA deadenylation and decapping followed by degradation of the mRNA body [1,2]. Mammalian ARE-containing transcripts are thought to be deadenylated by at least one of the seven known deadenylases and degraded mainly by the exosome, a multiprotein complex containing 3’-5’ exonucleases [1,2]. A relevant role in mRNA decay has been recently demonstrated for the 5’-3’ exonuclease Xrn1 [3]. ARE-binding proteins (ARE-BPs) are trans-acting factors responsible for the decay control of labile mRNAs [1]. Some ARE-BPs are decay-promoting factors (TTP, BRF1, KSRP), and others, such as HuR, are stabilizing factors, whereas AUFI promotes either decay or stabilization depending on the cellular context or its isoform expression profile [1]. According to the recently proposed recruitment model, destabilizing ARE-BPs interact with AREs and recruit the degradation machinery to the mRNA [4–6]. The ARE-BP KSRP, containing four contiguous K homology (KH) motifs that recognize the AREs and interact with the mRNA degradation machinery, promotes rapid decay of several ARE-containing mRNAs both in vitro and in vivo [4,6].

Activation of the stress-responsive c-Jun N-terminal kinase [7], p38 MAP kinase [8,9], MAPKAPK2 [10,11], phosphatidylinositol 3-kinase (PI3K)-AKT [12,13], and Wnt/β-catenin signaling [14] was shown to trigger stabilization of various transcripts, thereby causing large alterations in their abundance. We have previously shown that activation of the Wnt signaling pathway in pituitary T3-1 cells induces a coordinate transcriptional and post-transcriptional regulation of select target genes [14,15]. We proposed that the integrated regulation of transcription and mRNA turnover is required to ensure rapid and relevant changes in the expression of regulatory genes [9,14].

Recently, we observed that a common set of transcripts is stabilized by either treatment with lithium chloride (LiCl), a mimicker of Wnt signaling [16], or AKT activation in pituitary T3-1 cells (unpublished data). Among these transcripts, we found β-catenin. β-catenin plays a key role in embryonic development and tumorigenesis by controlling the expression of Wnt-responsive genes [17–19]. In response to Wnt signals, Dishevelled is recruited to the Axin complex to inhibit glycogen synthase kinase-3β, resulting in cytosolic accumulation and subsequent translocation of β-catenin to the nucleus, activating target genes.

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Abbreviations: ARE, AU-rich element; ARE-BPs, ARE-binding proteins; CAT, chloramphenicol acetyltransferase; KH, K homology; LCI, lithium chloride; LC/M5/M5, liquid chromatography–tandem mass spectrometry; Ly, Ly294002; MG, β3-microglobulin; myrAKT1, myristylated form of AKT1; PI3K, phosphatidylinositol 3-kinase; t½, half-life

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Author Summary

During mammalian development and adulthood, β-catenin regulates the transcription of a family of genes with multiple essential roles in cell proliferation and differentiation. β-catenin also plays a role in cancer when it carries mutations that result in uncontrolled β-catenin function. Here, we report that the lifetime of the β-catenin-encoding transcript is under regulatory control. We show that specific cellular signals relevant to proper mammalian development and implicated in tumor formation can prolong β-catenin transcript half-life, leading to the accumulation of β-catenin protein. We identify a molecular mechanism for this prolongation by showing that a protein factor responsible for β-catenin transcript instability (and thus degradation) is impaired by phosphorylation, a chemical modification. When this factor is impaired, β-catenin mRNA and protein accumulate. Our results point to an unanticipated control of β-catenin levels through regulation of its transcript half-life in response to signals related to proliferation and differentiation.

Results

β-Catenin Is Encoded by a Labile mRNA Whose Half-Life Is Prolonged by Wnt Signaling

We previously reported that the treatment of mouse pituitary αT3-1 cells with LiCl (a compound widely used to mimic Wnt signaling [16]) stabilizes select ARE-containing labile transcripts [14]. To identify additional ARE-containing transcripts whose mRNA t_½ is prolonged in αT3-1 cells in response to LiCl treatment, a large-scale analysis using the ARE-cDNA microarray system was performed [28]. The microarray screening revealed that LiCl treatment significantly upregulated, among others, β-catenin mRNA (unpublished data). By both semiquantitative and quantitative RT-PCR, we confirmed that β-catenin mRNA increased by approximately fourfold in cells treated with LiCl (Figure 1A and unpublished data). The inspection of mouse β-catenin 3' UTR revealed the presence of several U-rich regions spread over the entire sequence (classified as class III AREs (28 and references cited therein)). As shown in Figure 1B, quantitative PCR experiments demonstrated that β-catenin mRNA was unstable in intact αT3-1 cells displaying a t_½ of approximately 45 min, whereas the control β₂-microglobulin (β₂-MG) was stable. In order to verify whether β-catenin AREs were responsible for the rapid decay of the endogenous transcript, we transfected αT3-1 cells with a reporter plasmid containing the entire β-catenin 3' UTR placed at the 3' end of chloramphenicol acetyltransferase (CAT) sequence. As shown in Figure 1C, CAT-β-catenin chimeric transcript displayed a short t_½ while control CAT mRNA was stable.

Next, we investigated whether Wnt signaling activation regulates β-catenin mRNA turnover in intact cells. As shown in Figure 1D, LiCl treatment significantly prolonged the t_½ of β-catenin mRNA while the t_½ of β₂-MG was unaffected. Furthermore, treatment of αT3-1 cells with recombinant mouse Wnt-3A increased β-catenin mRNA steady-state levels (Figure 1E). Importantly, Wnt-3A treatment strongly prolonged β-catenin t_½ in intact cells (Figure 1F).

These results suggest that β-catenin mRNA is labile in unstimulated cells due to the presence of AREs in its 3' UTR. Wnt signaling activation stabilizes β-catenin mRNA and induces its accumulation.

PI3K-AKT Activation Stabilizes β-Catenin mRNA and Increases Both mRNA and Protein Steady-State Levels

As previously reported, besides mimicking the activation of the canonical Wnt pathway, LiCl also targets PI3K-AKT signaling [29,30]. Furthermore, the results of our ARE-cDNA microarray screening revealed that LiCl treatment and AKT activation, obtained expressing a constitutively active myr-stylated form of AKT1 (myrAKT1 [31]), induced stabilization of a common set of mRNAs including β-catenin (unpublished data). These observations prompted us to investigate the effect of PI3K-AKT activation on β-catenin mRNA turnover. First, we assessed the contribution given by PI3K-AKT pathway to LiCl-induced β-catenin mRNA stabilization. We used both pharmacological inhibitors and an AKT dominant negative mutant [AKT1(K179M)] to block PI3K-AKT signaling. We found that treatment with either LY294002 (LY, a PI3K inhibitor [32]) or triciribine (a specific AKT inhibitor [33]) strongly reduced LiCl-induced stabilization of β-catenin mRNA in intact αT3-1 cells (Figure 2A and 2B). Similarly, AKT1(K179M) expression impaired LiCl-induced stabilization of β-catenin mRNA in vitro (Figure 2C).

Next, we expressed myrAKT1 in αT3-1 cells. As shown in Figure 2D, the kinase activity immunoprecipitated with anti-AKT antibody was fivefold higher in αT3-1–myrAKT1 cells compared with control cells (Figure S1). Importantly, we observed a strong increase of β-catenin mRNA and protein levels in LiCl-treated αT3-1–myrAKT1 and C2C12–myrAKT1 cells compared with control cells (Figure 2E and 2F).

These results suggest that PI3K-AKT activation stabilizes β-catenin mRNA, leading to mRNA and protein accumulation.
Insulin-Induced PI3K-AKT Activation Stabilizes β-Catenin mRNA and Increases Both mRNA and Protein Steady-State Levels

In order to verify whether insulin-induced AKT activation affects β-catenin mRNA stabilization, we used insulin receptor-overexpressing HIRc-B rat cells, which display strong responses to insulin [13,34]. Indeed, the kinase activity immunoprecipitated with anti-AKT antibody was approximately sixfold higher in insulin-treated than in control HIRc-B cells, and LY treatment strongly reduced insulin-dependent AKT activation (Figure 3A). Figure 3B shows that insulin increased β-catenin mRNA steady-state levels and that LY treatment almost completely blocked insulin effect. β-catenin mRNA was significantly stabilized by insulin in intact HIRc-B cells, and LY treatment strongly decreased insulin-induced β-catenin mRNA stabilization (Figure 3C). Accordingly, insulin induced β-catenin protein accumulation in both cytosolic and nuclear fractions from HIRc-B cells (Figure 3D). To investigate whether insulin affects β-catenin protein degradation rate, we treated HIRc-B cells with cycloheximide, to inhibit translational elongation, and monitored β-catenin levels in total extracts after different intervals of time. As shown in Figure 3E, insulin did not affect the rate of β-catenin protein decay.

In conclusion, a physiological activation of PI3K-AKT signaling causes stabilization of β-catenin transcript and is independent of the degradation rate.
increases steady-state levels of both β-catenin mRNA and protein.

The mRNA Destabilizing Factor KSRP Is Phosphorylated by AKT

We hypothesized that AKT activation stabilizes β-catenin transcript by targeting the mRNA decay machinery. Among ARE-BPs known to affect mRNA turnover, only KSRP [4] and HuR [35] were able to specifically immunoprecipitate β-catenin mRNA in RNA-immunoprecipitation experiments (Figure 4A). We first investigated whether AKT was able to phosphorylate either KSRP or HuR. KSRP was phosphorylated by recombinant purified AKT2 in vitro, whereas HuR was not phosphorylated (Figure 4B). In silico analysis (Motif Scan, http://scansite.mit.edu/motifscan_seq.phtml) of the human KSRP primary sequence performed at medium stringency indicated serine 193 (bold in the following peptide: GLPERSVSLTGAPES) as a potential AKT phosphor-
ylation site (asterisk in Figure 4C, left). We evaluated the ability of AKT2 to phosphorylate KSRP deletion mutants expressed as GST-fusion proteins (Figure 4C). Only the KSRP fragments including KH1, where S193 is located, were phosphorylated by AKT2 in a concentration-dependent manner (Figure 4C, lanes 1, 3, 4, and 6, and unpublished data). Importantly, myrAKT1 expression enhanced the phosphorylation of coexpressed FLAG-KSRP while not affecting FLAG-KSRP(S193A) mutant, as shown by anti-FLAG immunoprecipitation following [32P]orthophosphate metabolic labeling of intact HeLa cells (Figure 4D). In order to unambiguously identify the KSRP residue(s) phosphorylated by AKT, recombinant human KSRP was phosphorylated by AKT2 in vitro, the gel band was digested with trypsin and

Figure 3. Insulin Stabilizes β-Catenin mRNA and Increases Its Expression

(A) HIRc-B cells were treated for 1 h with DMSO (control), insulin (10⁻⁶ M) plus DMSO, or LY (25 μM for 16 h) plus insulin. Total extracts were immunoprecipitated with either anti-AKT antibody or control IgG (clgG). Pellets were incubated (20 min at 30 °C) with histone 2B (H2B) in kinase buffer in the presence of [γ-32P]ATP. Labeled proteins were separated by SDS-PAGE and detected by autoradiography.

(B) Expression of β-catenin and β2-MG, monitored by RT-PCR, in control HIRc-B cells and in HIRc-B treated with either insulin or LY plus insulin.

(C) Quantitative RT-PCR analysis of both β-catenin and β2-MG transcripts in control HIRc-B cells, in HIRc-B treated with either insulin or LY plus insulin.

(D) Immunoblot analysis of either S100 or nuclear extracts from either control- or insulin-treated HIRc-B cells with anti-β-catenin, β-actin, and HDAC2 antibodies. The amount of each band was quantitated by densitometry and insulin was found to increase β-catenin expression by 3.2- and 2.1-fold over the control in S100 and nuclear extracts, respectively.

(E) HIRc-B cells were maintained for 16 h in DMEM containing 0.1% FCS; then either PBS (control) or insulin (10⁻⁶ M) was added for 1 h. Cultures were then treated with cycloheximide (50 μg/ml) for the indicated times. Total cell extracts were prepared, and the levels of β-catenin quantitated by immunoblotting and densitometric scanning. Results are the average (±SEM) of three experiments. β-Actin immunoblotting was used to verify the equal protein loading.

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enriched for phosphopeptides, and the peptides were analyzed by nanoflow liquid chromatography–tandem mass spectrometry (LC-MS/MS). This led to the identification of the unique peptide SV[pS]LTGAPESVQK with phosphorylation at the second serine residue (S193) (Figure 4E). The entire sequence of the phosphorylated peptide is perfectly conserved in several mammalian species (Mus musculus, Rattus norvegicus, Canis familiaris, and Bos taurus), and the phosphorylated serine is conserved, in a corresponding position, also in nonmammalian species (Gallus gallus, Xenopus laevis, and Danio rerio) (unpublished data). S193 was mutated to alanine in KH1-4 and KH1-2, and the mutant proteins were expressed in bacteria. As shown in Figure 4F, the S193A mutation abolished AKT-dependent phosphorylation in vitro.
Overall, these data suggest that AKT phosphorylates human KSRP at the unique site S193.

KSRP Controls β-Catenin mRNA Turnover in αT3-1 Cells

The results presented above indicated that KSRP was phosphorylated by AKT and led us to hypothesize that KSRP could be involved in AKT-induced stabilization of β-catenin mRNA. We and others demonstrated that KSRP regulates the stability of select mRNAs in response to different stimuli [9,36]. Thus, we investigated whether KSRP controls the decay rate of β-catenin mRNA. Stable knock-down of KSRP obtained using shRNA in αT3-1 cells (αT3-1–shKSRP, Figure 5A) led to a more than fourfold increase of the steady-state levels of β-catenin mRNA when compared to mock-transfected cells (Figure 5B). Furthermore, β-catenin mRNA was stable in αT3-1–shKSRP in vivo (Figure 5C) and in vitro (Figure S2A). Conversely, KSRP overexpression in αT3-1 cells blocked the LiCl-induced stabilization of β-catenin mRNA (Figure S2B). Importantly, β-catenin protein levels were approximately fourfold higher in αT3-1–shKSRP than in control cells, although β-catenin protein decay rates were unchanged (Figure 5D and 5E). The increase in β-catenin expression was mirrored by an increase in luciferase activity driven by two β-catenin-responsive reporters, TOP-FLASH and mouse c-myc promoter region (Figure 5F).

We ruled out the possibility that AKT activation could change KSRP expression levels affecting its protein stability. As shown in Figure S3, expression of myrAKT1 in αT3-1 cells did not affect either KSRP steady-state levels (Figure S3A) or protein stability (Figure S3B).

Altogether, these results indicate that KSRP is crucial in controlling β-catenin mRNA decay and, in turn, β-catenin expression.

14-3-3 Interacts with Phosphorylated KSRP and Affects Its Decay-Promoting Activity

To investigate the functional consequences of KSRP phosphorylation by AKT, we performed in vitro reconstitution experiments. Either nonphosphorylated or AKT2-phosphorylated KSRP was added to S100 extracts from αT3-1–shKSRP in typical in vitro degradation assays. As presented in Figure 6, KSRP promoted rapid decay of β-catenin mRNA, whereas AKT2-phosphorylated KSRP lacked its decay-promoting activity (Figure 6A). Similar results were obtained using KH1-4 as a GST fusion instead of the Baculovirus-expressed KSRP (Figure 6E). As predictable on the basis of the results shown in Figure 4F, the incubation of the mutant KH1-4(S193A) with AKT2 did not affect its β-catenin RNA decay-promoting activity (Figure 6A, lanes 17–28).

The sequence of the peptide including S193 closely resembles the phosphoserine-containing motif that is recognized by members of the 14-3-3 protein family [37]. Indeed, in a yeast two-hybrid screening performed in order to identify molecular partners of KSRP, we found, among others, the cDNA encoding 14-3-3ζ (unpublished data). To investigate whether phosphorylation by AKT favors the interaction of KSRP with 14-3-3, we cotransfected either myrAKT1 or the empty vector (mock) together with FLAG-KSRP [9] in 293T cells. The kinase activity immunoprecipitated by anti-AKT antibody was higher in myrAKT–293T than in mock 293T cells (unpublished data). Endogenous 14-3-3 coimmunoprecipitated with FLAG-KSRP only in cells transfected with myrAKT1 (Figure 6B). Accordingly, GST–KH1-4 pulled down endogenous 14-3-3 present in extracts from αT3-1 cells stably expressing myrAKT1 but not from mock αT3-1 cells (Figure 6C). As predictable on the basis of the position of the unique AKT phosphorylation site (S193), only GST-KSRP fusion proteins containing the KH1 interacted with 14-3-3 (Figure 6C, lanes 6, 9, and 10). We examined whether phosphorylated S193 is required for KSRP interaction with 14-3-3. Coimmunoprecipitation experiments showed that wild-type KSRP interacted with 14-3-3 when coexpressed with myrAKT1 in 293T cells, whereas KSRP(S193A) did not (Figure 6D). Accordingly, the S193A mutant KH1-4 [GST–KH1-4(S193A)] failed to interact with 14-3-3 in pull-down experiments (unpublished data). To inhibit the interaction between AKT-phosphorylated KSRP and 14-3-3, we used the synthetic peptide difopein, which binds to 14-3-3 proteins with high affinity and competitively inhibits 14-3-3–ligand interaction [38]. AKT2-phosphorylated KSRP was preincubated with either a scrambled peptide (control) or difopein, as indicated, before incubation with S100 extracts from αT3-1–shKSRP cells and used in in vitro RNA degradation experiments. Data presented in Figure 6E indicate that preincubation with difopein restored the decay-promoting activity of KH1-4, preventing the interaction of phosphorylated KH1-4 protein with 14-3-3 (Figure 6F).

Altogether, our results indicate that AKT-phosphorylated KSRP interacts with 14-3-3 and that this interaction impairs the decay-promoting activity of KSRP in vitro.

AKT Activation Impairs the Interaction of KSRP with the Exosome

We investigated whether the impairment of the mRNA decay-promoting activity of KSRP upon phosphorylation by AKT2 (see Figure 6A) was due to either reduced RNA binding or reduced interaction with the decay machinery. In vitro phosphorylation by AKT2 did not affect the β-catenin mRNA binding activity of KSRP either in the absence or in the presence of recombinant 14-3-3ζ (Figure 7A and 7B).

Coimmunoprecipitation experiments performed in 293T cells showed that expression of myrAKT1 impaired the interaction of KSRP with core exosome components including hRrp4p and hRrp41 and with the exosome-associated factor hMtr4p [39] (Figure 7C and unpublished data), whereas it did not affect the interaction with the deadenylase PARN. Similarly, in GST pull-down experiments, GST–KH1-4 interacted with hRrp4p and hMtr4p present in αT3-1 total extracts, whereas GST–KH1-4 phosphorylated in vitro by AKT2 failed to interact (Figure 7D). Difopein, competing the interaction between GST–KH1-4 and 14-3-3 (see Figure 6F), restored the ability of GST–KH1-4 to pull-down hRrp4p and hMtr4p (Figure 7E).

The evidence that myrAKT1 expression does not affect the interaction of KSRP with PARN prompted us to investigate whether β-catenin mRNA deadenylation was affected by myrAKT1 expression in αT3-1 cells. As shown in in vitro degradation experiments presented in Figure 7F, deadenylated β-catenin mRNA accumulated in αT3-1–myrAKT1 cells.

Our results suggest that phosphorylation by AKT and interaction with 14-3-3 affect the ability of KSRP to interact with the exosome.
Here we report that β-catenin is encoded by a labile transcript whose t½ is prolonged by Wnt and PI3K-AKT signaling. The mRNA decay-promoting factor KSRP is required to ensure rapid degradation of β-catenin transcript in unstimulated cells. AKT phosphorylates KSRP at a unique serine residue, creating a functional binding site for the molecular chaperone 14-3-3. As a consequence, AKT activation impairs KSRP ability to interact with the exoribonucleolytic complex exosome and, in turn, to promote rapid mRNA decay.

β-Catenin mRNA Is Labile and Its Degradation Rate Is Controlled by the ARE-BP KSRP

With its involvement in the Wnt signal transduction pathway and tumorigenesis, β-catenin is an extensively studied protein. However, the vast majority of studies focused on the control of β-catenin protein degradation upon its signal-induced phosphorylation [17–19]. Lopez de Silanes et al. [40] identified β-catenin mRNA as a target of the ARE-BP HuR in colon cancer cells, leading to the hypothesis that β-catenin is encoded by a labile mRNA. Our results demonstrate that β-catenin mRNA is labile in unstimulated cells and point to an unanticipated mechanism by which β-catenin expression can be regulated at the level of its mRNA turnover by PI3K-AKT activation. Knock-down experiments demonstrate that KSRP controls the t½ and the steady-state levels of β-catenin mRNA, thus increasing β-catenin protein levels and enhancing the β-catenin–dependent TOP-FLASH– and c-myc promoter–dependent reporter transcription. Notably, KSRP knock-down did not affect β-catenin protein degradation rate. While this manuscript was in preparation, a

Figure 5. KSRP Is Required for β-Catenin mRNA Degradation

(A) Immunoblot analysis of total extracts from either mock αT3-1 (empty pSUPER-Puro vector-transfected) or αT3-1-shKSRP (pSUPER-Puro-shKSRP–transfected) cells using affinity-purified anti-KSRP and anti-α-tubulin antibodies.
(B) Expression of β-catenin and β2-MG, monitored by RT-PCR, in either mock αT3-1 or αT3-1–shKSRP cells.
(C) Quantitative RT-PCR analysis of both β-catenin and β2-MG transcripts in either mock αT3-1 or αT3-1–shKSRP cells. Total RNA was isolated at the indicated times after the addition of actinomycin D. The values shown are averages (±SEM) of three independent experiments performed in duplicate.
(D) Immunoblot analysis of total extracts from the indicated cell lines with anti–β-catenin and α-tubulin antibodies.
(E) Either mock αT3-1 or αT3-1–shKSRP cells were treated with cycloheximide (50 μg/ml) for the indicated times. Total cell extracts were prepared and the levels of β-catenin quantitated by immunoblotting and densitometric scanning. Results are the average (±SEM) of three experiments. α-Tubulin immunoblotting was used to verify the equal protein loading.
(F) Either mock αT3-1 or αT3-1–shKSRP cells were transiently transfected with either TOP-FLASH or c-myc-LUC reporter vectors, cultured for 2 d, and collected, and luciferase activity was measured. The values shown are averages (±SEM) of four independent experiments performed in duplicate.

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Discussion

Here we report that β-catenin is encoded by a labile transcript whose t½ is prolonged by Wnt and PI3K-AKT signaling. The mRNA decay-promoting factor KSRP is required to ensure rapid degradation of β-catenin transcript in unstimulated cells. AKT phosphorylates KSRP at a unique serine residue, creating a functional binding site for the molecular chaperone 14-3-3. As a consequence, AKT activation impairs KSRP ability to interact with the exoribonucleolytic complex exosome and, in turn, to promote rapid mRNA decay.
report from Thiele et al. [41] described the presence of alternative splicing in the 3’ UTR of human β-catenin mRNA that could influence its stability. However, we exclude that alternatively spliced isoforms exist in the 3’ UTR of mouse β-catenin mRNA in αT3-1 and C2C12 cells (Figure S4 and unpublished data). Surprisingly, Thiele et al. [41] reported that AREs in the 3’ UTR of human β-catenin mRNA are stabilizing elements. Our results indicate that β-catenin transcript is unstable in four different cell lines (αT3-1, HIRc-B, C2C12 as presented in this report, and 293T, unpublished data) and that mouse β-catenin 3’ UTR confers instability to a reporter mRNA. These data are in agreement with the general view that AREs are destabilizing elements in unstimulated cells (reviewed in [1–3]).
PI3K-AKT Activation Prolongs β-Catenin mRNA Half-Life by Targeting KSRP

Our data suggest that PI3K-AKT signaling stabilizes β-catenin transcript targeting the mRNA decay machinery. In the past, conflicting results on PI3K-AKT–induced control of β-catenin protein degradation have been provided [42–45]. The discrepancies might depend on the divergent regulation of protein decay in different cell types. Indeed, we have observed that insulin-induced PI3K-AKT activation does not affect β-catenin protein stability in HIRc-B cells (Figure 3E),...
while myrAKT1 expression slightly prolongs β-catenin protein $t_{1/2}$ in αT3-1 cells (unpublished data). However, our results indicate that PI3K-AKT consistently induces β-catenin mRNA stabilization and protein accumulation in both cell lines. Even though our data indicate that PI3K-AKT activation, regulating the mRNA decay machinery, can lead to β-catenin protein accumulation in the absence of changes in its protein degradation rate, it is conceivable that an integrated control of both mRNA and protein stability could be required to ensure rapid and sustained changes of β-catenin expression in response to certain proliferative and differentiative cues. Notably, AKT-induced interaction of β-catenin protein with 14-3-3 has been shown to increase both β-catenin levels and its transcriptional activity [26]. Therefore, AKT-dependent interaction of 14-3-3 either with a factor involved in β-catenin mRNA turnover, such as KSRP, or with β-catenin itself can lead to accumulation of β-catenin protein. In a sense, 14-3-3 might be considered a biological switch controlling β-catenin expression at different levels.

KSRP, a major regulator of β-catenin mRNA decay, is phosphorylated by AKT at a unique residue (S193). It is a general concept that destabilizing ARE-BPs, including BRF1, KSRP, and TTP, are responsible for rapid decay of labile mRNAs in unstimulated cells recruiting the mRNA decay machinery [4–6]. We and others have previously shown that activation of the PI3K-AKT pathway controls the turnover of select mRNAs targeting either BRF1 or TTP and turning off their mRNA destabilizing function [12,13,46]. It is noteworthy that, in our experimental model, KSRP and HuR are the major ARE-BPs interacting with β-catenin mRNA. PI3K-AKT activation does not affect the expression level and the phosphorylation status of HuR while inducing KSRP phosphorylation. It is possible to hypothesize that a certain signaling pathway can affect the turnover of select mRNAs regulating the function of distinct ARE-BPs, depending on the cellular context. On the other hand, the activation of different pathways can affect the turnover of different sets of transcripts targeting the same ARE-BP. In C2C12 myoblasts, MAPK p38 activation prolongs the $t_{1/2}$ of select myogenic transcripts inhibiting KSRP function [9], whereas PI3K-AKT activation does not affect the stability of the same mRNAs (unpublished data). Similarly, p38 activation in αT3-1 cells does not affect the $t_{1/2}$ of β-catenin mRNA (unpublished data).

How the decay of distinct sets of transcripts can be specifically regulated by different signaling pathways that target the same ARE-BP is still an unsolved issue.

KSRP Interacts with 14-3-3 in a Serine 193-Dependent Way

Our data indicate that KSRP phosphorylation by PI3K-AKT creates a functional 14-3-3 binding site. Our current and previous findings, together with existing literature [13,47,48], suggest that 14-3-3 family members play a regulatory role on the function of some destabilizing ARE-BPs.

Phosphorylation by AKT, followed by interaction with 14-3-3, impairs the ability of KSRP to promote β-catenin mRNA decay, reducing KSRP interaction with the 3′-5′ exoribonuclease complex exosome while leaving unaffected the ability of KSRP to interact with the mRNA. The results obtained using the high-affinity 14-3-3 competitor peptide difopein suggest that KSRP–14-3-3 interaction is implicated in this process. Unexpectedly, we found that AKT activation does not affect KSRP interaction with the deadenylase PARN and that deadenylated β-catenin mRNA accumulates when incubated with S100 from αT3-1-myrAKT1 cells in vitro (unpublished data). Similarly, p38 activation induces a transcriptional change in 14-3-3 expression at different levels.

The four KH domains that constitute the central core of the KSRP are all necessary to ensure its interaction with the entire decay-promoting machinery [6]. S193 lies in the first KH domain of KSRP. Therefore, it is not surprising that the structural changes likely produced by phosphorylation, and the consequent interaction with 14-3-3, severely impair the β-catenin mRNA decay-promoting function of KSRP.

In conclusion, the expression levels of β-catenin have to be tightly regulated. As the amount of β-catenin rises, it accumulates in the nucleus, where it interacts with specific transcription factors, leading to regulation of target genes. Inappropriate activation of the β-catenin pathway is linked to a wide range of cancers, including colorectal cancer and melanoma. On the other hand, AKT has emerged as a crucial regulator of widely divergent cellular processes including apoptosis, differentiation, and metabolism. Disruption of normal AKT signaling has now been documented as a frequent occurrence in several human cancers, and it appears to play an important role in their progression. The results we obtained point to KSRP phosphorylation as a link between PI3K-AKT signaling and the control of β-catenin mRNA $t_{1/2}$ and, consequently, of its expression. PI3K-AKT signaling activation, with consequent KSRP phosphorylation and functional deactivation, might contribute to sustain β-catenin accumulation and, as a result, activation of target genes potentially able to accelerate tumor development.

Materials and Methods

Reagents. IY and insulin were obtained from Sigma (http://www.sigmaaldrich.com); tricarbide, from Calbiochem/EMD Biosciences (http://www.emdbiosciences.com); Wnt-3A, from R&D Systems (http://www.rndsystems.com); and histone 2B, from Roche (http://www.roche.com).

Plasmids. cDNA fragments containing mouse β-catenin cDNA fragments (as shown in Figure S1) and GAPDH 3′ UTR (nucleotides 580–810) were subcloned into PstI-XbaI–restricted pCY2 [39]. A cDNA fragment containing the coding region of human KSRP (nucleotides 202-2136) was cloned into the EcoRI-Xhol sites of pCMV-Tag2B vector (Stratagene, http://www.stratagene.com) in frame with the FLAG sequence to obtain a FLAG-KSRP plasmid. Mutagenesis was performed using FLAG-KSRP and the QuickChange Site-Directed Mutagenesis kit (Stratagene) to obtain FLAG-KSRP(S193A). HA-myrAKT1 cassette was excised from the plasmid previously described by Andjelkovic et al. [31] and subcloned into pcDNA3 (Invitrogen, http://www.invitrogen.com) to obtain pcMV-myr-AKT1, AKT1(K175M) [50] in pUSamp plasmid, and TOP-Firefly expression vectors were from Upstate Biotechnology (http://www.upstate.com). Murine c-myc promoter (~1,100 ± 580) fused with Luciferase was previously described [51]. To generate pCAT–β-catenin 3′ UTR,
we cloned the entire mouse β-catenin 3' UTR into the NotI-XbaI-restricted pcDNA3-CAT plasmid [4].

**Recombinant proteins and antibodies.** Affinity-purified human KSRP, expressed using the Baculovirus system, was described in Briata et al. [9]. GST-KSRP deletion mutants were previously described [4]. Amino acid 193 was methanoxylated using the Quick-Changing Site-Directed Mutagenesis Kit (Stratagene) to obtain KSRP-H1(K193A) and GST-KSRP-H1(S193A), respectively. GST–14-3-3 plasmid was constructed cloning the entire coding sequence of mouse 14-3-3ε into a pGEX vector.

Mouse monoclonal anti-14-3-3ε (K-19, which recognizes all the 14-3-3 family members), anti-14-3-3εta (C-16, ε-specific), anti-HuR monoclonal antibody 3A2, and anti-HDAC2 were obtained from Santa Cruz Biotechnology (http://www.scbt.com); mouse anti-GST was from Chemicon (http://www.chemicon.com); rabbit anti-AKT was from Cell Signaling (http://www.cellsignal.com); mouse anti-β-catenin was from Transduction Laboratories (http://www.transductionlabs.com); anti-KSRP antibody [4] was affinity purified and interacted with both human and rodent KSRP [4,14, and R. Gherzi, unpublished data]; and anti-hMtr4p [38] was generated against a hMtr4p(1–369)-GST fusion protein and affinity purified. Anti-AUF1 and anti-hRNPA1 were a gift from Dr. Gideon Dreyfuss (Howard Hughes Medical Institute), and anti-PARN, anti-hKrp41, anti-hKrp4p, and anti-TTP polyclonal antibodies were gifts from Drs. Elmar Wahle (University of Halle), Ger Prujin (Nijmegen Center for Molecular Life Science), David Grunstein (Wellcome Trust Centre for Gene Regulation and William Rigby (Dartmouth Medical School), respectively. Anti-FLAG (M2), anti-α-tubulin, and anti-β-actin monoclonal antibodies were from Sigma.

**Cells and transfections.** Murine T3-1 pituitary cells, rat HIRc-B fibroblasts, human HEK-293T cells (293T), and human HeLa cells were cultured in DMEM plus 10% FBS and sted with tryptophan. pcDNA3-CAT and murine cDNA21 were cultured in DMEM plus 20% FBS. Cell transfections were performed using LipofectAMINE Plus (Invitrogen), and G418 was selected. Transient transfections of pcDNA3-CAT or pcDNA3-CAT–β-catenin plasmids were performed as described in [4] with the exception that LipofectAMINE Plus was used.

**Semi-quantitative and quantitative RT-PCR.** Cells under different culture conditions were treated with 5 μg/ml actinomycin D and harvested at the indicated times, and total RNA was isolated using RNeasy Mini Kit (Qiagen, http://www.qiagen.com) and treated with DNase I (Promega, http://www.promega.com) according to the manufacturer's instructions. First-strand cDNA was obtained with Transcriptor Reverse Transcriptase (Roche).

For semi-quantitative RT-PCR, 250 ng of total RNA was retrotranscribed using oligo-dT primer. β-MG was used as an internal control for normalizing transcripts levels measured by RT-PCR. To optimize RT-PCR, preliminary dose-response experiments were performed to determine the range of first-strand cDNA concentrations at which PCR amplification was linear for each target molecule essentially as reported in Briata et al. [9]. For each species of RNA analyzed, the amount of RT-PCR product (measured as densitometric units) was plotted against the input of first-strand cDNA.

For quantitative RT-PCR, 150 ng of DNase I-treated total RNA was retrotranscribed using random examers and PCRs were performed using the IQ Sybr Green Mix Super (Bio-Rad, http://www.bio-rad.com) and the MiniOpticon Real-Time PCR Detection System (Bio-Rad). The sequence-specific primers used for PCRs are listed in Table S1. RNA in vitro degradation and UV-crosslinking. 32P-Labeled RNAs were synthesized and used as substrates for in vitro degradation assays as reported [7]. UV-crosslinking experiments were performed as described [7].

**Immunoprecipitation of ribonucleoprotein complexes.** Ribonucleoprotein complexes were immunoprecipitated from T3-1 cell lysates as previously described [7]. Total RNA, extracted from either immunocomplexes or total cell lysates (input), was subjected to RT-PCR. Primers are listed in Table S1.

In vitro kinase assays and 32P orthophosphate metabolic labeling. AKT kinase assays were performed using preactivated enzymes purchased from Upstate Biotechnology (50 ng of the active enzyme/reaction) as recommended by manufacturer. γ-[32P]ATP (3,000 Ci/mmol) was from Amersham Biosciences (http://www. amersham.com). In vivo 32P orthophosphate metabolic labeling of transiently transfected HeLa cells was performed as previously described [52], incubating cells with orthophosphate for 10 h.

**Isolation of phosphopeptides and LC-MS/MS and MS² analysis.** Purified recombinant KSRP was phosphorylated by AKT2 in standard kinase assays. The reactions were analyzed by gel electrophoresis; bands were excised with trypsin, and enriched for phosphopeptides using titanium dioxide microcolumns; and the peptides were analyzed by automated nanoflow LC-MS/MS with a method where the neutral loss of the phosphate group activate the acquisition of a second fragment ion spectrum (an MS² spectrum) as previously described in detail [53]. All MSMS spectra files from each LC run were centroided and merged to a single file, which was searched using the Mascot search engine (Matrix Science, http://www.matrixscience.com) against the publicly available human database.

**shRNA-mediated KSRP knock-down.** pSUPER-Puro-shKSRP was previously described [9]. T3-1 cells were transfected using LipofectAMINE Plus (Invitrogen). Transfectant pools were selected with 0.3 μg/ml puromycin (Sigma).

**Luciferase assays.** Transient transfections of either mock T3-1 or T3-1–shKSRP were carried out with LipofectAMINE Plus (Invitrogen). Luciferase activity was determined after 48 h with the Dual Luciferase System (Promega) following the indications of the manufacturer and using pRL-SV40 as a normalizing vector.

**Supporting Information**

**Figure S1.** β-Catenin mRNA Is Stabilized by myrAKT1 Expression In Myoblasts C2C12
(A) In vitro RNA degradation assays using 5100s from either mock C2C12 or C2C12 cells expressing myrAKT1. Internally 32P-labeled and capped RNA substrates were incubated with 5100s for the indicated times, and their decay was analyzed as described in Materials and Methods.
(B) Semi-quantitative RT-PCR analysis of β-catenin mRNA in either mock C2C12 cells or C2C12 cells expressing myrAKT1. Total RNA was isolated as indicated after the addition of actinomycin D. The amount of each transcript was quantitated by densitometry and plotted using a linear regression program. The values shown are averages (±SEM) of three independent experiments performed in duplicate.

Found at doi:10.1371/journal.pbio.0050005.s001 (442 KB TIF).

**Figure S2.** KSRP Controls β-Catenin mRNA Decay In Vitro
(A) In vitro RNA degradation assays using 5100s from either mock-transfected (empty pSUPER-Puro vector) T3-1 (mock T3-1) or pSUPER-Puro-shKSRP-transfected T3-1 cells (T3-1–shKSRP).
(B) In vitro RNA degradation assays using 5100s from either LiCl-treated mock-transfected T3-1 cells or LiCl-treated FLAG-KSRP-transfected T3-1 cells. Internally 32P-labeled and capped RNA substrates were incubated with 5100s for the indicated times, and their decay was analyzed as described in Materials and Methods.

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**Figure S3.** Neither KSRP Steady-State Levels nor Protein Stability Is Affected by AKT1 Activation
(A) Immunoblot analysis of total extracts from the indicated cell lines with anti-KSRP and β-tubulin antibodies.
(B) Neither mock T3-1 or T3-1–myrAKT1 cells were treated with cycloheximide (50 μg/ml) for the indicated times. Total cell extracts were prepared and the levels of KSRP were quantitated by immunoblotting and densitometric scanning. Results are the average (±SEM) of three experiments. β-Tubulin immunoblotting was used to verify the equal protein loading.

Found at doi:10.1371/journal.pbio.0050005.s003 (341 KB TIF).

**Figure S4.** A Single mRNA Form Contains the Entire 3' UTR of Mouse β-Catenin
RT-PCR analysis of total RNA from either mock T3-1 cells (untreated or treated as indicated) or T3-1–myrAKT1. The primers used are listed in Table S1 and schematically represented on the left.

Found at doi:10.1371/journal.pbio.0050005.s004 (467 KB TIF).

**Table S1.** Primers Used for RT-PCRs
The primers used for RT-PCRs were m-β-catenin (mouse β-catenin), m-AKT1 (mouse AKT1), r-β-catenin (rat β-catenin), b-C (the entire 3'
UTR of mouse β-catenin, mβ2-MG (mouse β2-MG), rβ2-MG (rat β2-MG), CAT; CAT-β-catenin (the entire 3′ UTR of mouse β-catenin placed at the 3′ of CAT), mβ-cat Q-PCR (mouse β-catenin for quantitative PCRs), and mβ2-MG G-PCR (mouse β2-MG for quantitative PCRs).

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References


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