

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

Roberto Gherzi¹*, Michele Trabucchi¹, Marco Ponassi¹, Tina Ruggiero¹, Giorgio Corte^{1,2}, Christoph Moroni³, Ching-Yi Chen⁴, Khalid S. Khabar⁵, Jens S. Andersen⁶, Paola Briata¹

1 Istituto Nazionale per la Ricerca sul Cancro, Genova, Italy, **2** Department of Biology, Oncology, and Genetics, University of Genova, Genova, Italy, **3** Institute for Medical Microbiology, University of Basel, Basel, Switzerland, **4** Department of Biochemistry and Molecular Genetics, University of Alabama at Birmingham, Birmingham, Alabama, United States of America, **5** King Faisal Specialist Hospital and Research Center, Riyadh, Saudi Arabia, **6** Center for Experimental Bioinformatics, University of Southern Denmark, Odense, Denmark

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.

Citation: Gherzi R, Trabucchi M, Ponassi M, Ruggiero T, Corte G, et al. (2007) The RNA-binding protein KSRP promotes decay of β -catenin mRNA and is inactivated by PI3K-AKT signaling. *PLoS Biol* 5(1): e5. doi:10.1371/journal.pbio.0050005

Introduction

The half-life ($t_{1/2}$) 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 AUF1 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 α 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 α 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-3 β , resulting in cytosolic accumulation and subsequent translocation of β -catenin to

Academic Editor: Marv Wickens, University of Wisconsin, United States of America

Received July 25, 2006; **Accepted** November 3, 2006; **Published** December 19, 2006

Copyright: © 2007 Gherzi et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Abbreviations: ARE, AU-rich element; ARE-BPs, ARE-binding proteins; CAT, chloramphenicol acetyltransferase; KH, K homology; LiCl, lithium chloride; LC-MS/MS, liquid chromatography–tandem mass spectrometry; LY, LY294002; β 2-MG, β 2-microglobulin; myrAKT1, myristylated form of AKT1; PI3K, phosphatidylinositol 3-kinase; $t_{1/2}$, half-life

* To whom correspondence should be addressed. E-mail: rgherzi@ucsd.edu

© These authors contributed equally to this work.

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.

the nucleus, where it binds to transcription factors of the T-cell factor/lymphoid enhancer factor family and transactivates Wnt target genes [17,18]. Serine/threonine kinases belonging to the AKT family are major effectors of the PI3K pathway and are activated by insulin and other polypeptide growth factors [20,21]. The recruitment of AKT to the plasma membrane by the lipid products of PI3K leads to AKT phosphorylation and activation [20,21]. Once activated, AKT exerts a central role in metabolism, cell survival, motility, transcription, and cell-cycle progression [21–23]. Cross-talks between Wnt and PI3K-AKT signaling pathways have been described [24–27].

In this report, we describe that β -catenin mRNA is labile due to destabilizing elements located in its 3' UTR and that KSRP is a major molecular determinant of β -catenin mRNA instability. β -catenin transcript can be stabilized by either Wnt or PI3K-AKT signaling activation. AKT phosphorylates KSRP at a unique serine residue favoring its interaction with the adaptor protein 14-3-3. As a consequence, KSRP fails to interact with the exosome and, in turn, β -catenin mRNA is stabilized.

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 α T3-1 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 $t_{1/2}$ is prolonged in α T3-1 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, quantita-

tive PCR experiments demonstrated that β -catenin mRNA was unstable in intact α T3-1 cells displaying a $t_{1/2}$ of approximately 45 min, whereas the control β_2 -microglobulin (β_2 -MG) was stable. In order to verify whether β -catenin AREs were responsible for the rapid decay of the endogenous transcript, we transfected α T3-1 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 $t_{1/2}$ 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 $t_{1/2}$ of β -catenin mRNA while the $t_{1/2}$ of β_2 -MG was unaffected. Furthermore, treatment of α T3-1 cells with recombinant mouse Wnt-3A increased β -catenin mRNA steady-state levels (Figure 1E). Importantly, Wnt-3A treatment strongly prolonged β -catenin $t_{1/2}$ 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 myristylated 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 α T3-1 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 α T3-1 cells. As shown in Figure 2D, the kinase activity immunoprecipitated with anti-AKT antibody was fivefold higher in α T3-1–myrAKT1 than in mock α T3-1 cells, thus demonstrating that active AKT kinase was present in extracts from cells expressing myrAKT1. The steady-state levels of β -catenin mRNA were increased and β -catenin mRNA $t_{1/2}$ was prolonged in α T3-1–myrAKT1 cells (Figure 2E and 2F). myrAKT1 expression produced a similar stabilization of β -catenin mRNA in murine C2C12 myoblasts (C2C12–myrAKT1, Figure S1). Importantly, we observed a strong increase of β -catenin protein levels in both nuclear and cytosolic compartments of α T3-1–myrAKT1 and C2C12–myrAKT1 cells compared with control cells (Figure 2G and unpublished data).

These results suggest that PI3K-AKT activation stabilizes β -catenin mRNA, leading to mRNA and protein accumulation.

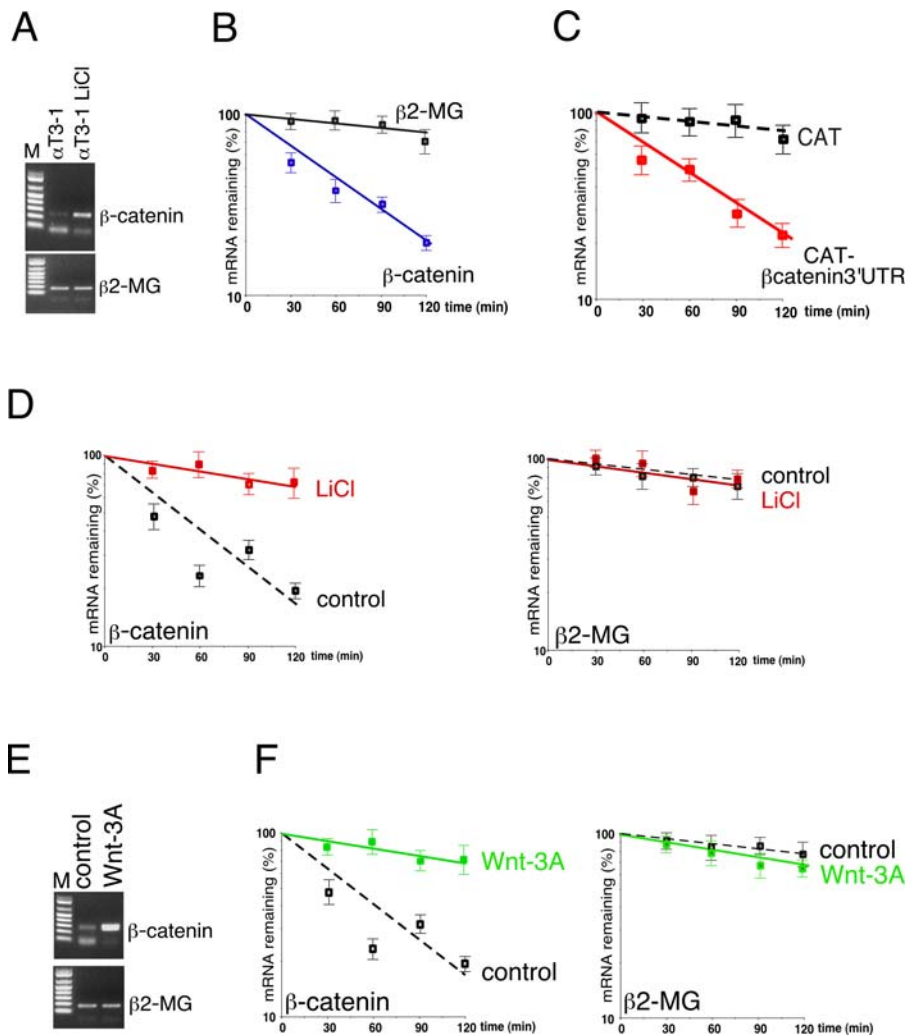


Figure 1. mRNA Encoding β -Catenin Is Labile and Is Stabilized by LiCl and Wnt-3A

(A) Expression of β -catenin and β 2-MG (control transcript), monitored by RT-PCR, in control and in LiCl-treated (20 mM for 6 h) α T3-1 cells.
 (B) Quantitative RT-PCR analysis of both β -catenin and β 2-MG transcripts in α T3-1 cells. Total RNA was isolated at the indicated times after addition of actinomycin D. The values shown are averages (\pm SEM) of three independent experiments performed in duplicate.
 (C) Quantitative RT-PCR analysis of both CAT and CAT- β -catenin transcripts in either CAT or CAT- β -catenin transiently transfected α T3-1 cells. Total RNA was isolated at the indicated times after addition of actinomycin D. The values shown are averages (\pm SEM) of three independent experiments performed in duplicate.
 (D) Semiquantitative RT-PCR analysis of both β -catenin and β 2-MG transcripts in either control or LiCl-treated α T3-1 cells. Total RNA was isolated at the indicated times 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 (\pm SEM) of three independent experiments performed in duplicate.
 (E) Expression of β -catenin and β 2-MG, monitored by RT-PCR, in either control-treated α T3-1, or Wnt-3A-treated (10 ng/ml, 6 h) α T3-1 cells.
 (F) Semiquantitative RT-PCR analysis of both β -catenin and β 2-MG transcripts in either control or Wnt-3A-treated α T3-1 cells. Total RNA was isolated at the indicated times after the addition of actinomycin D. The amount of each transcript was quantitated and represented as described in (D).
 doi:10.1371/journal.pbio.0050005.g001

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

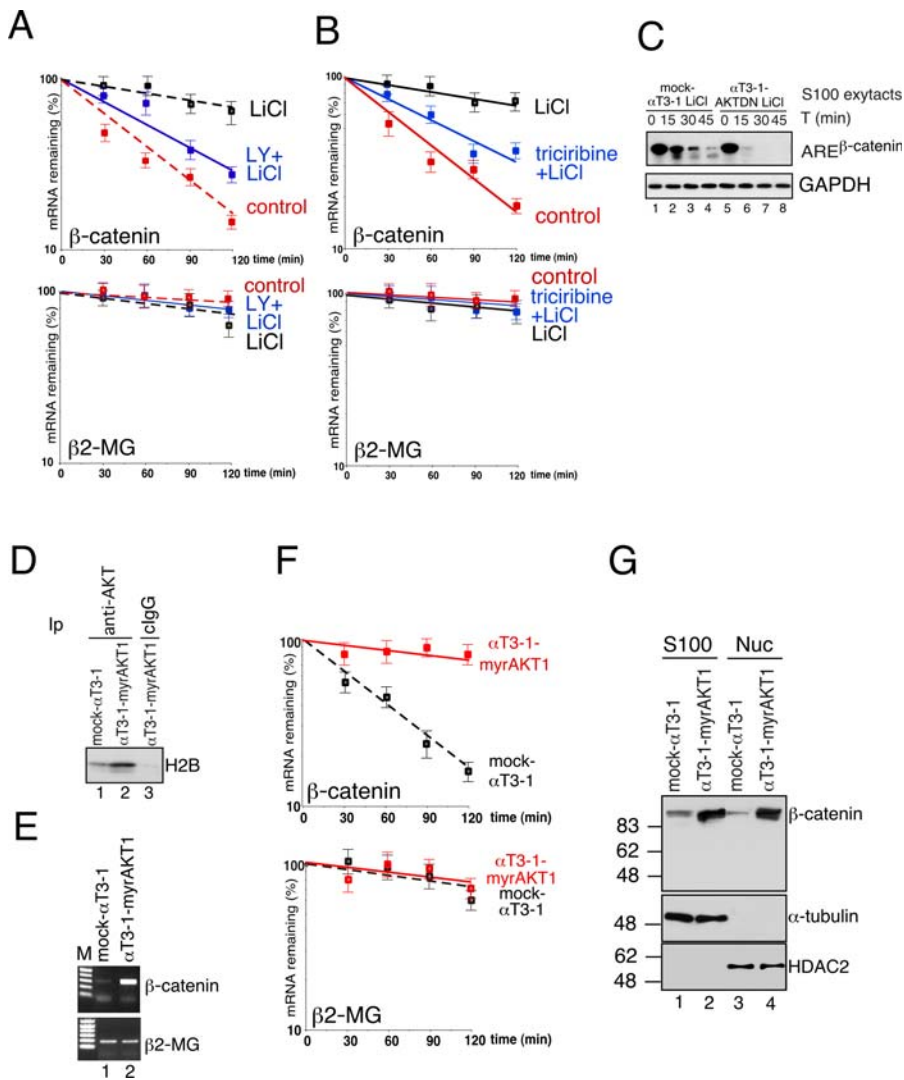


Figure 2. PI3K-AKT Signaling Stabilizes β -Catenin mRNA and Increases Its Expression

(A) Quantitative RT-PCR analysis of both β -catenin and β 2-MG transcripts in α T3-1 cells treated with either DMSO (the solvent of LY, control), DMSO plus LiCl, or LY (25 μ M for 16 h) plus LiCl. Total RNA was isolated at the indicated times after the addition of actinomycin D. The values shown are averages (\pm SEM) of three independent experiments performed in duplicate.

(B) Quantitative RT-PCR analysis of both β -catenin and β 2-MG transcripts in α T3-1 cells treated with either DMSO (the solvent of triciribine, control), DMSO plus LiCl (20 mM for 6 h), or triciribine (1 μ M for 1 h) plus LiCl. Total RNA was isolated at the indicated times after the addition of actinomycin D. The values shown are averages (\pm SEM) of three independent experiments performed in duplicate.

(C) In vitro RNA degradation assays using S100s from either LiCl-treated mock α T3-1 or LiCl-treated α T3-1 cells expressing the AKT dominant negative mutant AKT1(K179M) (α T3-1-AKTDN). Internally 32 P-labeled and capped RNA substrates were incubated with S100s for the indicated times and their decay analyzed as described in Materials and Methods.

(D) Either mock α T3-1 or α T3-1-myrAKT1 cells were lysed and total extracts were immunoprecipitated (ip) with either anti-AKT antibody or control IgG (cIgG). Pellets were incubated (20 min at 30 $^{\circ}$ C) with histone 2B (H2B) in kinase buffer in the presence of [γ - 32 P]ATP. Labeled proteins were separated by SDS-PAGE and detected by autoradiography.

(E) Expression of β -catenin and β 2-MG, monitored by RT-PCR, in either mock α T3-1 or α T3-1-myrAKT1 cells.

(F) Quantitative RT-PCR analysis of both β -catenin and β 2-MG transcripts in either mock α T3-1 or α T3-1-myrAKT1 cells. Total RNA was isolated at the indicated times after addition of actinomycin D. The values shown are averages (\pm SEM) of three independent experiments performed in duplicate.

(G) Immunoblot analysis of either S100 or nuclear extracts from the indicated cell lines with anti- β -catenin, α -tubulin, and HDAC2 antibodies.

doi:10.1371/journal.pbio.0050005.g002

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-

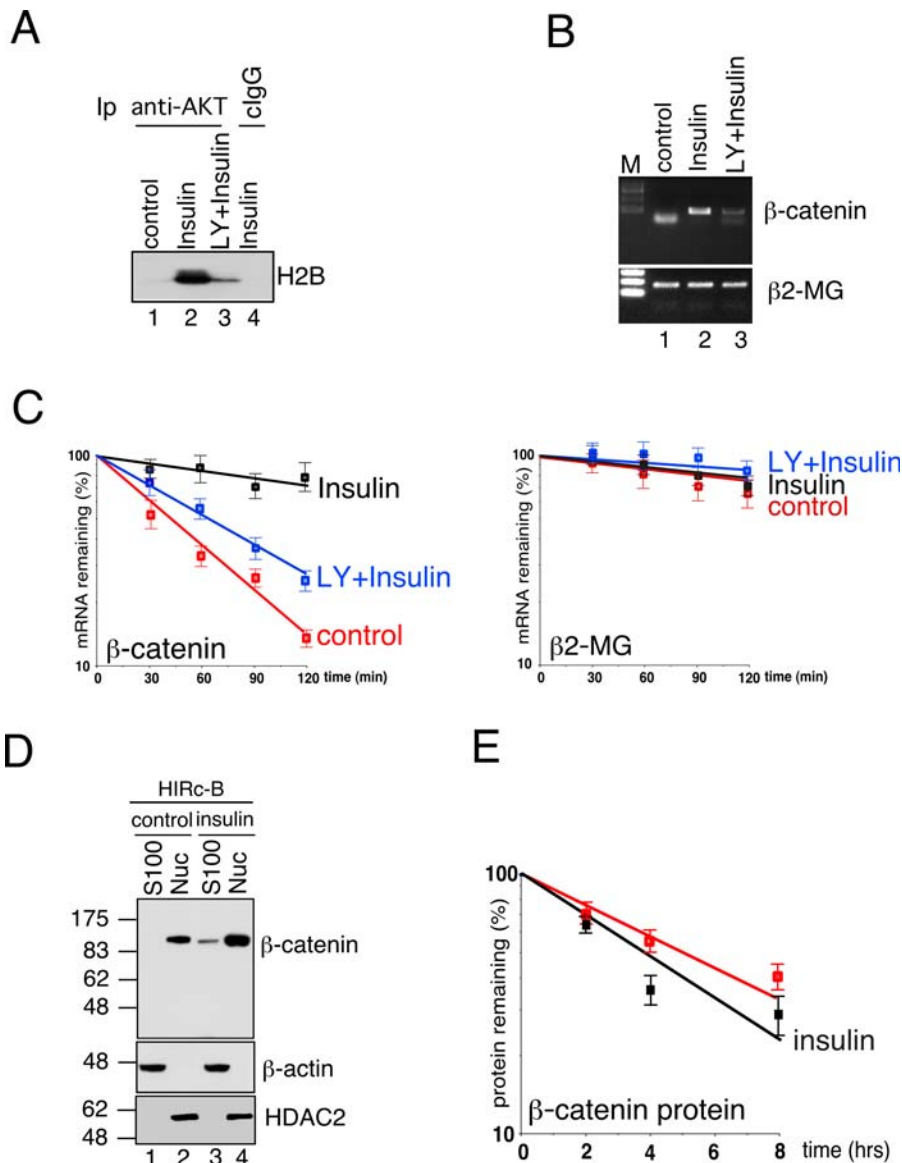


Figure 3. Insulin Stabilizes β -Catenin mRNA and Increases Its Expression

(A) HIRc-B cells were treated for 1 h with DMSO (control), insulin (10^{-6} M) plus DMSO, or LY (25 μ M 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 $^{\circ}$ C) with histone 2B (H2B) in kinase buffer in the presence of [γ - 32 P]ATP. Labeled proteins were separated by SDS-PAGE and detected by autoradiography.

(B) Expression of β -catenin and β 2-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 β 2-MG transcripts in control HIRc-B cells, in HIRc-B treated with either insulin or LY plus insulin. Total RNA was isolated at the indicated times after the addition of actinomycin D. The values shown are averages (\pm SEM) of three independent experiments performed in duplicate.

(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 μ g/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 (\pm SEM) of three experiments. β -Actin immunoblotting was used to verify the equal protein loading.

doi:10.1371/journal.pbio.0050005.g003

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 [32 P]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

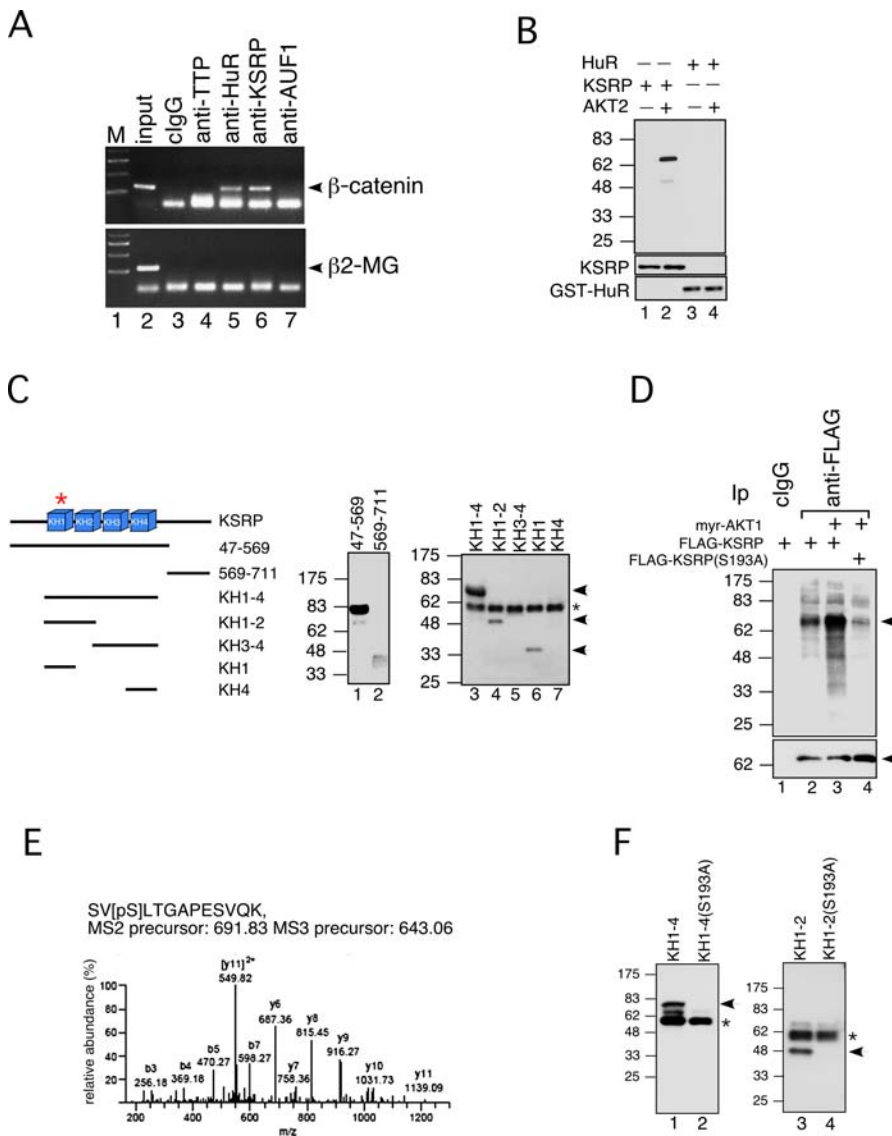


Figure 4. KSRP Is Phosphorylated by AKT in Serine 193

(A) Immunoprecipitation of β -catenin RNA-containing ribonucleoprotein complexes. The proteins were immunoprecipitated from α T3-1 total cell extracts using the indicated antibodies. RNA was extracted from the immune complexes and analyzed by RT-PCR as indicated.

(B) Either highly purified recombinant human KSRP (lanes 1 and 2) or affinity-purified GST-HuR (lanes 3 and 4) was incubated with either active recombinant AKT2 in kinase buffer or buffer alone in the presence of [γ - 32 P]ATP. Labeled proteins were separated by SDS-PAGE, blotted to nylon membranes, and detected by autoradiography (top panel). Immunoblot analysis of the above kinase reactions with either anti-KSRP (middle panel) or anti-GST (bottom panel) antibodies.

(C) Schematic representation of KSRP and GST-fused deletion mutants. Asterisks indicate the position of a putative AKT phosphorylation site (left). AKT2 kinase assays were performed using the indicated recombinant protein substrates (middle and right). Arrows point to the position of each phosphorylated protein; the asterisk marks the position of phosphorylated AKT2.

(D) In vivo [32 P]orthophosphate metabolic labeling of HeLa cells transiently cotransfected with either FLAG-KSRP plus empty pcDNA3, or FLAG-KSRP plus pCMV-myr-AKT1, or FLAG-KSRP(S193A) plus pCMV-myr-AKT1. Aliquots of the lysates were immunoprecipitated with protein A-sepharose-bound mouse control IgG (clgG) or anti-FLAG antibody, separated by SDS-PAGE, and autoradiographed (top panel). Immunoblot analysis of the above in vivo phosphorylation reactions with anti-FLAG antibody (bottom panel). Arrows point to the position of transfected KSRP.

(E) MS-MS fragmentation spectrum of the tryptic peptide SV[pS]LTGAPESVQK of KSRP showing phosphorylation of S193.

(F) AKT2 kinase assays using the indicated recombinant protein substrates. Arrows point to the position of each phosphorylated protein; the asterisk marks the position of phosphorylated AKT2.

doi:10.1371/journal.pbio.0050005.g004

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 α T3-1 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 α T3-1 cells (α T3-1-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 α T3-1-shKSRP in vivo (Figure 5C) and in vitro (Figure S2A). Conversely, KSRP overexpression in α T3-1 cells blocked the LiCl-induced stabilization of β -catenin mRNA (Figure S2B). Importantly, β -catenin protein levels were approximately fourfold higher in α T3-1-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 α T3-1 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 α T3-1-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 ability (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 14-3-3 ζ (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 α T3-1 cells stably expressing myrAKT1 but not from mock α T3-1 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 α T3-1-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 14-3-3 ζ (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 α T3-1 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 α T3-1 cells. As shown in in vitro degradation experiments presented in Figure 7F, deadenylated β -catenin mRNA accumulated in α T3-1-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.

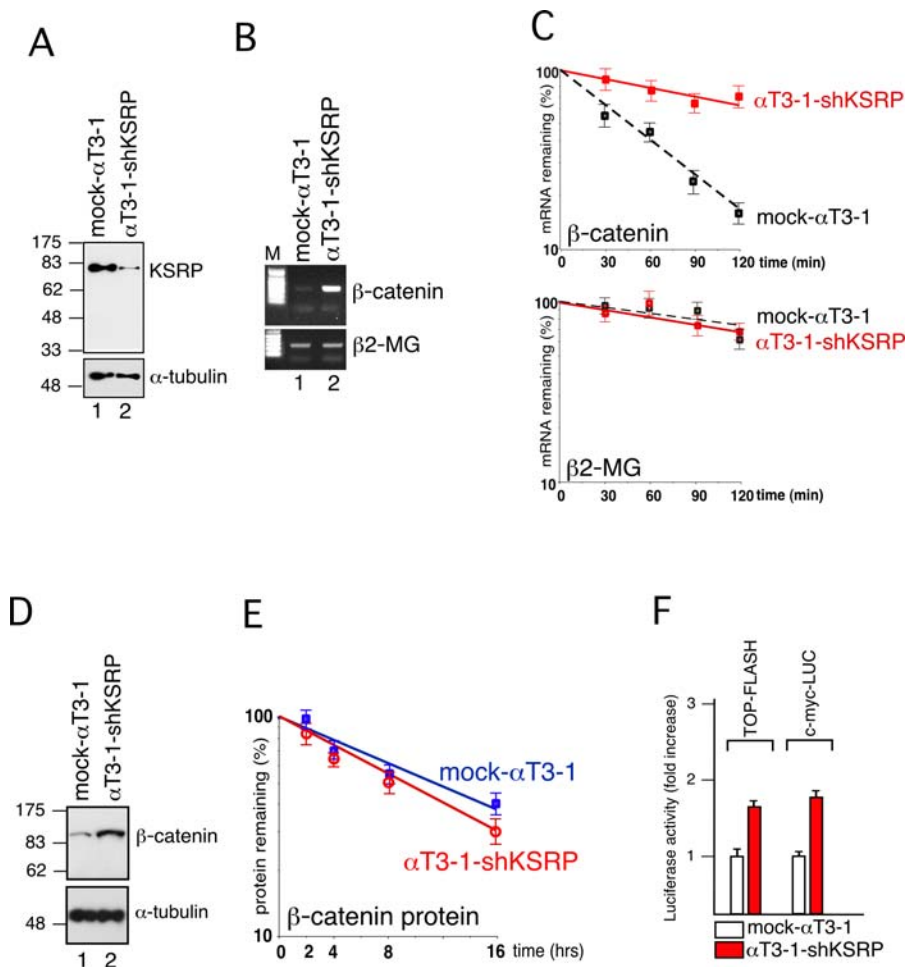


Figure 5. KSRP Is Required for β -Catenin mRNA Degradation

(A) Immunoblot analysis of total extracts from either mock α T3-1 (empty pSUPER-Puro vector-transfected) or α T3-1-shKSRP (pSUPER-Puro-shKSRP-transfected) cells using affinity-purified anti-KSRP and anti- α -tubulin antibodies.

(B) Expression of β -catenin and β 2-MG, monitored by RT-PCR, in either mock α T3-1 or α T3-1-shKSRP cells.

(C) Quantitative RT-PCR analysis of both β -catenin and β 2-MG transcripts in either mock α T3-1 or α T3-1-shKSRP cells. Total RNA was isolated at the indicated times after the addition of actinomycin D. The values shown are averages (\pm 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 α T3-1 or α T3-1-shKSRP cells were treated with cycloheximide (50 μ g/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 (\pm SEM) of three experiments. α -Tubulin immunoblotting was used to verify the equal protein loading.

(F) Either mock α T3-1 or α T3-1-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 (\pm SEM) of four independent experiments performed in duplicate.

doi:10.1371/journal.pbio.0050005.g005

Discussion

Here we report that β -catenin is encoded by a labile transcript whose $t_{1/2}$ 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 $t_{1/2}$ 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

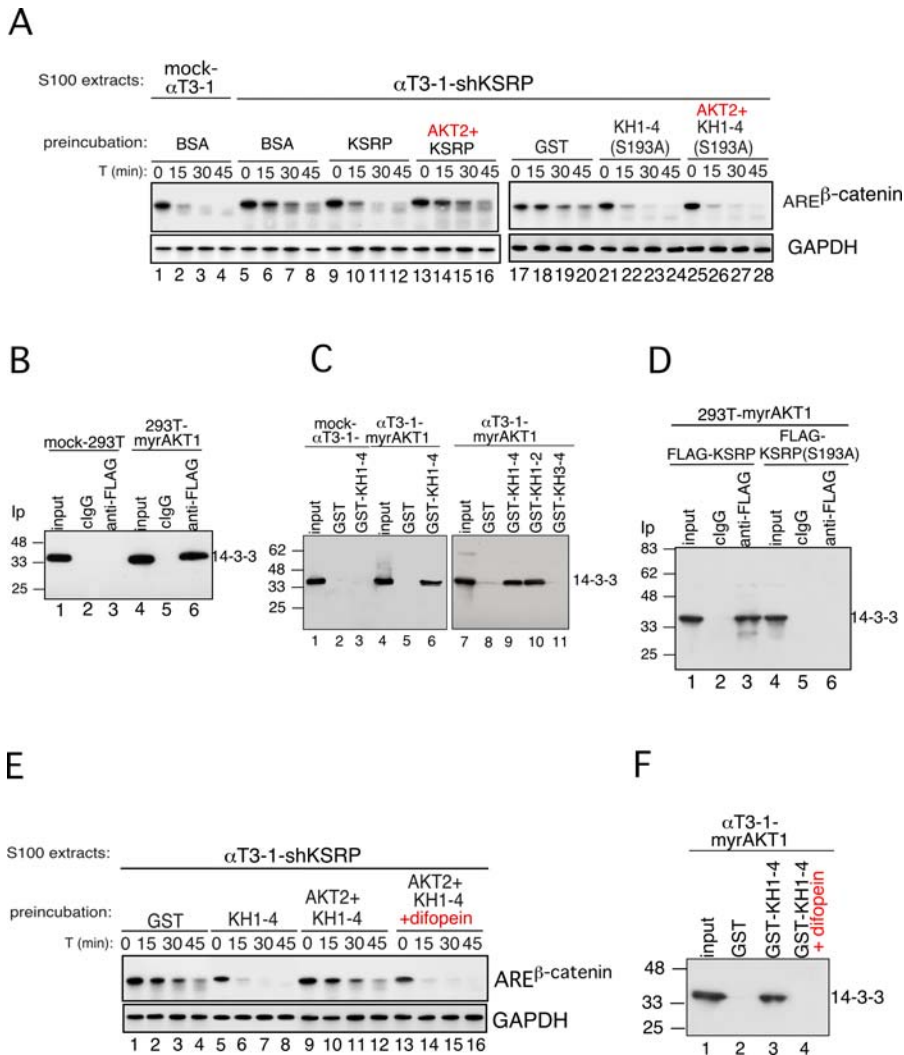


Figure 6. KSRP Phosphorylation by AKT Promotes Its Interaction with 14-3-3 and Affects Its mRNA-Destabilizing Function

(A) In vitro RNA degradation assays using S100s from either mock α T3-1 (lanes 1–4) or α T3-1-shKSRP cells (lanes 5–8) preincubated with BSA (lanes 1–4), GST (lanes 17–20), KSRP (30 nM, lanes 9–12), AKT2-phosphorylated KSRP (30 nM, lanes 13–16), KH1-4 (S193A) (30 nM, lanes 21–24), or AKT2-phosphorylated KH1-4(S193A) (30 nM, lanes 25–28), respectively. Internally 32 P-labeled and capped RNA substrates were added, and their decay was monitored as described above.

(B) Coimmunoprecipitation of FLAG-KSRP and endogenous 14-3-3 in 293T cells transiently transfected with FLAG-KSRP and either pCMV empty vector (mock 293T) or pCMV-myrAKT1 (293T-myrAKT1). Cell lysates were immunoprecipitated as indicated and analyzed by immunoblotting using anti-14-3-3 antibody.

(C) GST pull-down of endogenous 14-3-3 from total extracts of either mock α T3-1 (lanes 1–3) or α T3-1-myrAKT1 (lanes 4–11) cells using either control GST, GST-KH1-4, or the additional KSRP deletion mutants fused with GST (as indicated, see Figure 4B for a schematic representation of KSRP deletion mutants). Proteins were analyzed by immunoblotting using anti-14-3-3 antibody.

(D) Coimmunoprecipitation of either FLAG-KSRP or FLAG-KSRP(S193A) and endogenous 14-3-3 in 293T cells transiently transfected with pCMV-myrAKT1 (293T-myrAKT1) and either FLAG-KSRP or FLAG-KSRP(S193A). Cell lysates were immunoprecipitated as indicated and analyzed by immunoblotting using anti-14-3-3 antibody.

(E) In vitro RNA degradation assays using S100s from α T3-1-shKSRP cells preincubated with either GST (lanes 1–4), KH1-4 (30 nM, lanes 5–8), AKT2-phosphorylated KH1-4 (30 nM, lanes 9–12), or AKT2-phosphorylated KH1-4 (30 nM) preincubated with difopein (50 nM) (lanes 13–16), respectively. Internally 32 P-labeled and capped RNA substrates were added, and their decay monitored as described above.

(F) GST pull-down of endogenous 14-3-3 from total extracts of α T3-1-myrAKT1 cells using either control GST, GST-KH1-4, or GST-KH1-4 preincubated with 50 nM difopein (as indicated). Proteins were analyzed by immunoblotting using anti-14-3-3 antibody.

doi:10.1371/journal.pbio.0050005.g006

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 α T3-1 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 (α T3-1, 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]).

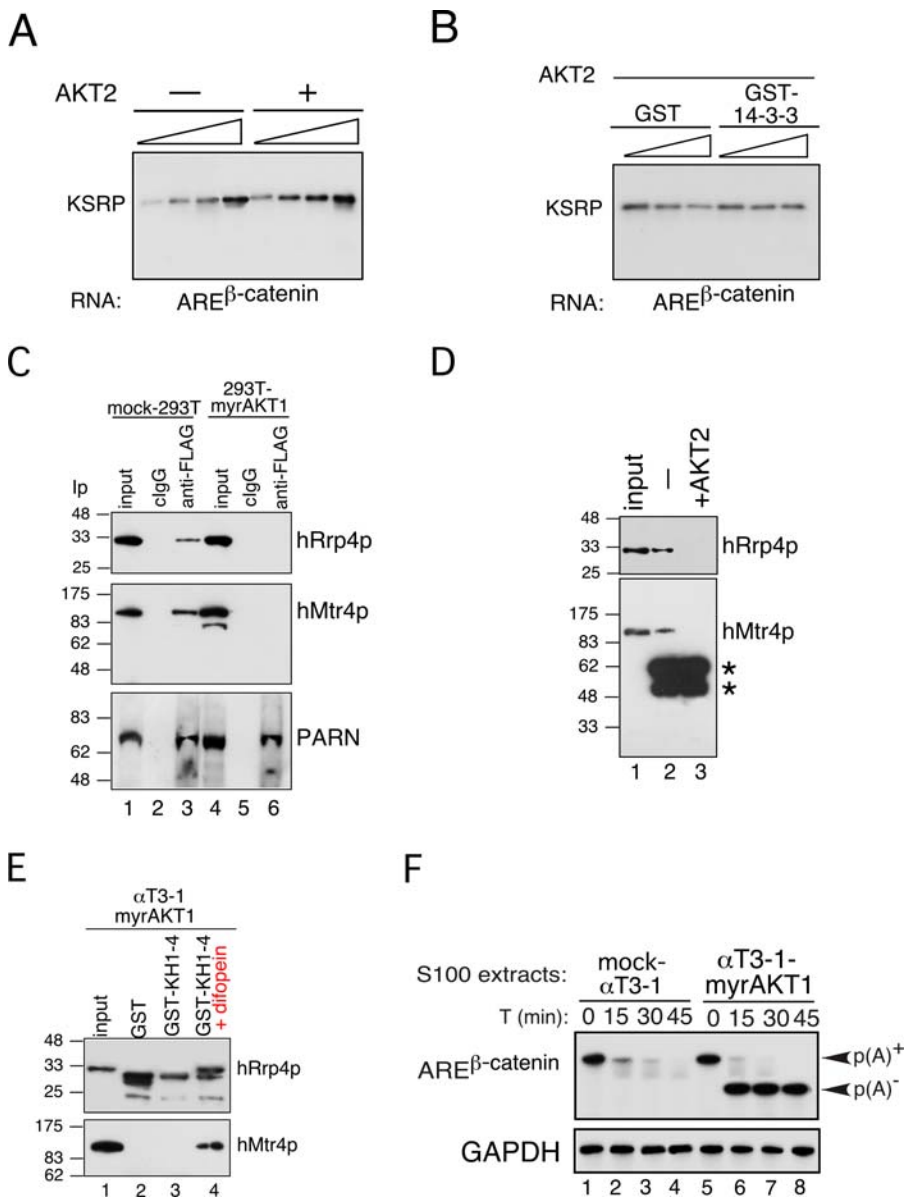


Figure 7. AKT Activation Affects KSRP-Exosome Interaction

(A) The interaction between ^{32}P -labeled ARE β -catenin RNA and recombinant purified KSRP (increasing amounts from 30 to 300 nM) subjected to kinase reactions in the absence or in the presence of AKT2 (as indicated) was evaluated by UV-crosslinking.

(B) The interaction between ^{32}P -labeled ARE β -catenin RNA and recombinant purified KSRP (50 nM) subjected to AKT2 phosphorylation in the presence of either GST (50 nM) or GST-14-3-3 (50 nM, as indicated) was evaluated by UV-crosslinking.

(C) Coimmunoprecipitation of FLAG-KSRP and either endogenous exosome components (hRrp4p and hMtr4p, as indicated) or endogenous deadenylase PARN in 293T cells transiently transfected with FLAG-KSRP and either pCMV empty vector (mock-293T) or pCMV-myrAKT1 (293T-myrAKT1). Cell lysates were immunoprecipitated as indicated and analyzed by immunoblotting using the indicated antibodies.

(D) GST pull-down of endogenous hRrp4p and hMtr4p from total extracts of $\alpha\text{T3-1}$ cells using GST-KH1-4 subjected to kinase reaction either in the absence or in the presence of AKT2. Proteins were analyzed by immunoblotting using the indicated antibodies. Asterisks indicate antibody cross-reactivity with GST-fusion proteins.

(E) GST pull-down of endogenous hRrp4p and hMtr4p from total extracts of $\alpha\text{T3-1}$ -myrAKT1 cells using either control GST, GST-KH1-4, or GST-KH1-4 preincubated with 50 nM difopein (as indicated). Proteins were analyzed by immunoblotting using either anti-hRrp4p or anti-hMtr4p antibodies.

(F) In vitro RNA degradation assays using S100s from either mock $\alpha\text{T3-1}$ or $\alpha\text{T3-1}$ -myrAKT1 cells. Internally ^{32}P -labeled, capped, and polyadenylated β -catenin and GAPDH RNA substrates were incubated with S100s for the indicated times, and their decay was analyzed as described in Materials and Methods. Arrows point to either poly(A) $^{+}$ or poly(A) $^{-}$ β -catenin RNA species.

doi:10.1371/journal.pbio.0050005.g007

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 α T3-1 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 α T3-1 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' exoribonucleolytic 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 α T3-1-myrAKT1 cells in *in vitro* degradation assays. We previously demonstrated that KSRP associates with mRNA decay enzymes, including PARN and the exosome components [4,39]. However, our recent data indicate that, although PARN is involved in the decay of a reporter mRNA by tethered KSRP, it does not appear to play a major role in the process while tethered KSRP primarily relies on exosome function [6]. Thus, our present results are in keeping with the idea that the exosome complex is the main enzymatic machine recruited by KSRP to the RNA [6]. It is noteworthy that a large-scale proteomic analysis identified three exosome components (hRrp4p, hRrp41p, and hRrp45) and the exosome-associated helicase hMtr4p, as well as KSRP itself, as molecular partners of 14-3-3 [49].

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. LY and insulin were obtained from Sigma (<http://www.sigmaaldrich.com>); triciribine, 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-XhoI 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(K179M) [50] in pUSEamp plasmid, and TOP-FLASH expression vectors were from Upstate Biotechnology (<http://www.upstate.com>). Murine c-myc promoter (–1,100 \pm 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 mutagenized using the Quick-Change Site-Directed Mutagenesis kit (Stratagene) to obtain GST-KH1-2(S193A) and GST-KH1-4(S193A), respectively. GST-14-3-3 plasmid was constructed cloning the entire coding sequence of mouse 14-3-3 ζ into a pGEX vector.

Mouse monoclonal anti-14-3-3 β (K-19, which recognizes all the 14-3-3 family members), anti-14-3-3zeta (C-16, ζ -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 BD Transduction Laboratories (<http://www.bdbiosciences.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-AUFI and anti-hnRNP-A1 were a gift from Dr. Gideon Dreyfuss (Howard Hughes Medical Institute), and anti-PARN, anti-hRrp41, anti-hRrp4p, and anti-TTP polyclonal antibodies were gifts from Drs. Elmar Wahle (University of Halle), Ger Pruijn (Nijmegen Center for Molecular Life Sciences), David Tollervey (Wellcome Trust Centre for Cell Biology), 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 α 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 murine C2C12 myoblasts were cultured in DMEM plus 20% FBS. Cell transfections were performed using LipofectAMINE Plus (Invitrogen), and G418 (Invitrogen) was used at 500 to 800 μ g/ml (depending on the cell line) for selection. Cell pools of transfectants were used for experiments. α T3-1 cells were starved in DMEM plus 0.5% FBS for 16 h prior to LiCl treatment, and α T3-1-myrAKT1 cells were starved in DMEM plus 0.5% FBS for 16 h prior to experiments. HIRc-B cells were starved in DMEM plus 0.1% FBS for 16 h prior to experiments or further treatments. Transient transfections of α T3-1 with either pcDNA3-CAT or pcDNA3-CAT- β -catenin plasmids were performed as described in [4] with the exception that LipofectAMINE Plus was used.

Semiquantitative and quantitative RT-PCR. Cells under different culture conditions were treated with 5 μ g/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 semiquantitative RT-PCR, 250 ng of total RNA was retrotranscribed using oligo-dT primer. β 2-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 eximers 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. 32 P-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 α T3-1 cell lysates as previously described [7]. Total RNA, extracted from either immunocomplexes or total cell lysates (input), was subjected to RT-PCRs. Primers are listed in Table S1.

In vitro kinase assays and 32 P orthophosphate metabolic labeling. AKT (1 and 2) kinase assays were performed using preactivated enzymes purchased from Upstate Biotechnology (50 ng of the active enzyme/reaction) as recommended by manufacturer. [γ - 32 P]ATP (3,000 Ci/mmol) was from Amersham Biosciences (<http://www.amersham.com>).

In vivo 32 P orthophosphate metabolic labeling of transiently transfected HeLa cells was performed as previously described [52], incubating cells with orthophosphate for 16 h.

Isolation of phosphopeptides and LC-MS/MS and MS³ analysis. Purified recombinant KSRP was phosphorylated by AKT2 in standard kinase assays. The reactions were analyzed by gel electrophoresis; bands were excised, digested 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 MS³ spectrum) as previously described in detail [53]. All MS/MS 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]. α T3-1 cells were transfected using LipofectAMINE Plus (Invitrogen). Transfectant pools were selected with 0.3 μ g/ml puromycin (Sigma).

Luciferase assays. Transient transfections of either mock α T3-1 or α 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 S100s from either mock C2C12 or C2C12 cells expressing myrAKT1. Internally 32 P-labeled and capped RNA substrates were incubated with S100s for the indicated times, and their decay was analyzed as described in Materials and Methods.

(B) Semiquantitative 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 (\pm SEM) of three independent experiments performed in duplicate.

Found at doi:10.1371/journal.pbio.0050005.sg001 (442 KB TIF).

Figure S2. KSRP Controls β -Catenin mRNA Decay In Vitro

(A) In vitro RNA degradation assays using S100s from either mock-transfected (empty pSUPER-Puro vector) α T3-1 (mock α T3-1) or pSUPER-Puro-shKSRP-transfected α T3-1 cells (α T3-1-shKSRP).

(B) In vitro RNA degradation assays using S100s from either LiCl-treated mock-transfected α T3-1 cells or LiCl-treated FLAG-KSR-transfected α T3-1 cells. Internally 32 P-labeled and capped RNA substrates were incubated with S100s for the indicated times, and their decay was analyzed as described in Materials and Methods.

Found at doi:10.1371/journal.pbio.0050005.sg002 (792 KB TIF).

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 α -tubulin antibodies.

(B) Either mock α T3-1 or α T3-1-myrAKT1 cells were treated with cycloheximide (50 μ g/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 (\pm SEM) of three experiments. α -Tubulin immunoblotting was used to verify the equal protein loading.

Found at doi:10.1371/journal.pbio.0050005.sg003 (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 α T3-1 cells (untreated or treated as indicated) or α 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.sg004 (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), m- β 2-MG (mouse β 2-MG), r- β 2-MG (rat β 2-MG), CAT; CAT- β -catenin (the entire 3' UTR of mouse β -catenin placed at the 3' of CAT), m- β -cat Q-PCR (mouse β -catenin for quantitative PCRs, and m- β 2-MG q-PCR (mouse β 2-MG for quantitative PCRs).

Found at doi:10.1371/journal.pbio.0050005.st001 (35 KB DOC).

Acknowledgments

We are indebted to Drs. D. Tollervey, E. Wahle, G. Pruijn, G. Dreyfuss, W. Rigby, and A. Nicolin for reagents and antibodies.

References

- Wilusz CJ, Wilusz J (2004) Bringing the role of mRNA decay in the control of gene expression into focus. *Trends Genet* 20: 491–497.
- Meyer S, Temme C, Wahle E (2004) Messenger RNA turnover in eukaryotes: Pathways and enzymes. *Crit Rev Biochem Mol Biol* 39: 197–216.
- Newbury SF (2006) Control of mRNA stability in eukaryotes. *Biochem Soc Trans* 34: 30–34.
- Gherzi R, Lee KY, Briata P, Wegmuller D, Moroni C, et al. (2004) A KH domain RNA binding protein, KSRP, promotes ARE-directed mRNA turnover by recruiting the degradation machinery. *Mol Cell* 14: 571–583.
- Lykke-Andersen J, Wagner E (2005) Recruitment and activation of mRNA decay enzymes by two ARE-mediated decay activation domains in the proteins TTP and BRF-1. *Genes Dev* 19: 351–361.
- Chou CF, Mulky A, Maitra S, Lin WJ, Gherzi R, et al. (2006) Tethering KSRP, a decay-promoting AU-rich element-binding protein, to mRNA elicits mRNA decay. *Mol Cell Biol* 26: 3695–3706.
- Chen C-Y, Gherzi R, Andersen JS, Gaietta G, Jürchott K, et al. (2000) Nucleolin and YB-1 are required for JNK-mediated interleukin-2 mRNA stabilization during T-cell activation. *Genes Dev* 14: 1236–1248.
- Frevel MA, Bakheet T, Silva AM, Hissong JG, Khabar KS, et al. (2003). p38 mitogen-activated protein kinase-dependent and independent signaling of mRNA stability of AU-rich element-containing transcripts. *Mol Cell Biol* 23: 425–436.
- Briata P, Forcales SV, Ponassi M, Corte G, Chen C-Y, et al. (2005) p38-dependent phosphorylation of the mRNA decay-promoting factor KSRP controls the stability of select myogenic transcripts. *Mol Cell* 20: 891–903.
- Dean JL, Sully G, Clark AR, Saklatvala J (2004) The involvement of AU-rich element-binding proteins in p38 mitogen-activated protein kinase pathway-mediated mRNA stabilisation. *Cell Signal* 16: 1113–1121.
- Gaestel M (2006) MAPK kinases—MKs: Two's company, three's a crowd. *Nat Rev Mol Cell Biol* 7: 120–130.
- Ming X-F, Stoecklin G, Lu M, Looser R, Moroni C (2001) Parallel and independent regulation of interleukin-3 mRNA turnover by phosphatidylinositol 3-kinase and p38 mitogen-activated protein kinase. *Mol Cell Biol* 21: 5778–5789.
- Schmidlin M, Lu M, Leuenberger SA, Stoecklin G, Mallaun M, et al. (2004) The ARE-dependent mRNA destabilizing activity of BRF1 is regulated by protein kinase B. *EMBO J* 23: 4760–4769.
- Briata P, Ilengo C, Corte G, Moroni C, Rosenfeld MG, et al. (2003) The Wnt/ β -catenin>Pitx2 pathway controls the turnover of Pitx2 and other unstable mRNAs. *Mol Cell* 12: 1201–1211.
- Kioussi C, Briata P, Back SH, Rose DW, Hamblet NS, et al. (2002) Identification of a Wnt/Dvl/ β -catenin \rightarrow Pitx2 pathway mediating cell-type-specific proliferation during development. *Cell* 111: 673–685.
- Hedgepeth CM, Conrad LJ, Zhang J, Huang HC, Lee VM, et al. (1997) Activation of the Wnt signaling pathway, a molecular mechanism for lithium action. *Dev Biol* 185: 82–91.
- Miller JR, Moon RT (1996) Signal transduction through β -catenin and specification of cell fate during embryogenesis. *Genes Dev* 10: 2527–2539.
- Cadigan KM, Nusse R (1997) Wnt signaling, a common theme in animal development. *Genes Dev* 11: 3286–3305.
- Reya T, Clevers H (2005) Wnt signalling in stem cells and cancer. *Nature* 434: 843–850.
- Fayard E, Tintignac LA, Baudry A, Hemmings BA (2005) Protein kinase B/Akt at a glance. *J Cell Sci* 118: 5675–5678.
- Woodgett JR (2005) Recent advances in the protein kinase B signaling pathway. *Curr Opin Cell Biol* 17: 150–157.
- Whiteman EL, Cho H, Birnbaum MJ (2002) Role of Akt/protein kinase B in metabolism. *Trends Endocrinol Metab* 13: 444–451.
- Brazil DP, Yang ZZ, Hemmings BA (2004) Advances in protein kinase B signalling: AKTion on multiple fronts. *Trends Biochem Sci* 29: 233–242.
- Fukumoto S, Hsieh CM, Maemura K, Layne MD, Yet SF, et al. (2001) Akt participation in the Wnt signaling pathway through Dishevelled. *J Biol Chem* 276: 17479–17483.
- Desbois-Mouthon C, Cadoret A, Blivet-Van Eggelpoel MJ, Bertrand F, Cherqui G, et al. (2001) Insulin and IGF-1 stimulate the β -catenin pathway through two signalling cascades involving GSK-3 β inhibition and Ras activation. *Oncogene* 20: 252–259.
- Tian Q, Feetham MC, Tao WA, He XC, Li L, et al. (2004) Proteomic analysis identifies that 14-3-3 ζ interacts with β -catenin and facilitates its activation by Akt. *Proc Natl Acad Sci U S A* 101: 15370–15375.
- Almeida M, Han L, Bellido T, Manolagas SC, Kousteni S (2005) Wnt proteins prevent apoptosis of both uncommitted osteoblast progenitors and differentiated osteoblasts by β -catenin-dependent and -independent signaling cascades involving Src/ERK and phosphatidylinositol 3-kinase/AKT. *J Biol Chem* 280: 41342–41351.
- Bakheet T, Williams BR, Khabar KS (2006) ARED 3.0: The large and diverse AU-rich transcriptome. *Nucleic Acids Res* 34: D111–D114.
- Chalecka-Franaszek E, Chuang DM (1999) Lithium activates the serine/threonine kinase Akt-1 and suppresses glutamate-induced inhibition of Akt-1 activity in neurons. *Proc Natl Acad Sci U S A* 96: 8745–8750.
- Sinha D, Wang Z, Ruchalski KL, Levine JS, Krishnan S, et al. (2005). Lithium activates the Wnt and phosphatidylinositol 3-kinase Akt signaling pathways to promote cell survival in the absence of soluble survival factors. *Am J Physiol Renal Physiol* 288: F703–F713.
- Andjelkovic M, Alessi DR, Meier R, Fernandez A, Lamb NJ, et al. (1997) Role of translocation in the activation and function of protein kinase B. *J Biol Chem* 272: 31515–31524.
- Vlahos CJ, Matter WF, Hui KY, Brown RF (1994) A specific inhibitor of phosphatidylinositol 3-kinase, 2-(4-morpholinyl)-8-phenyl-4H-1-benzopyran-4-one (LY294002). *J Biol Chem* 269: 5241–5248.
- Yang L, Dan HC, Sun M, Liu Q, Sun XM, et al. (2004) Akt/protein kinase B signaling inhibitor-2, a selective small molecule inhibitor of Akt signaling with antitumor activity in cancer cells overexpressing Akt. *Cancer Res* 64: 4394–4399.
- McClain DA, Maegawa H, Lee J, Dull TJ, Ulrich A, et al. (1987) A mutant insulin receptor with defective tyrosine kinase displays no biologic activity and does not undergo endocytosis. *J Biol Chem* 262: 14663–14671.
- Brennan CM, Steitz JA (2001) HuR and mRNA stability. *Cell Mol Life Sci* 58: 266–277.
- Linker K, Pautz A, Fechir M, Hubrich T, Greeve J, et al. (2005) Involvement of KSRP in the post-transcriptional regulation of human iNOS expression-complex interplay of KSRP with TTP and HuR. *Nucleic Acids Res* 33: 4813–4827.
- Yaffe MB, Rittinger K, Volinia S, Caron PR, Aitken A, et al. (1997). The structural basis for 14-3-3:phosphopeptide binding specificity. *Cell* 91: 961–971.
- Wang B, Yang H, Liu YC, Jelinek T, Zhang L, et al. (1999) Isolation of high-affinity peptide antagonists of 14-3-3 proteins by phage display. *Biochemistry* 38: 12499–12504.
- Chen C-Y, Gherzi R, Ong SE, Chan EL, Rajmakers R, et al. (2001) AU binding proteins recruit the exosome to degrade ARE-containing mRNAs. *Cell* 107: 451–464.
- Lopez de Silanes I, Fan J, Yang X, Zonderman AB, Potapova O, et al. (2003) Role of the RNA-binding protein HuR in colon carcinogenesis. *Oncogene* 22: 7146–7154.
- Thiele A, Nagamine Y, Hauschildt S, Clevers H (2006) AU-rich elements and alternative splicing in the β -catenin 3' UTR can influence the human β -catenin mRNA stability. *Exp Cell Res* 312: 2367–2378.
- Yuan H, Mao J, Li L, Wu D (1999) Suppression of glycogen synthase kinase activity is not sufficient for leukemia enhancer factor-1 activation. *J Biol Chem* 274: 30419–30423.
- Ding VW, Chen RH, McCormick F (2000) Differential regulation of glycogen synthase kinase 3 β by insulin and Wnt signaling. *J Biol Chem* 275: 32475–32481.
- Haq S, Michael A, Andreucci M, Bhattacharya K, Dotto P, et al. (2003) Stabilization of β -catenin by a Wnt-independent mechanism regulates cardiomyocyte growth. *Proc Natl Acad Sci U S A* 100: 4610–4615.
- Segrelles C, Moral M, Lara MF, Ruiz S, Santos M, et al. (2006) Molecular determinants of Akt-induced keratinocyte transformation. *Oncogene* 25: 1174–1185.
- Marderosian M, Sharma A, Funk AP, Vartanian R, Masri J, et al. (2006) Tristetraprolin regulates cyclin D1 and c-Myc mRNA stability in response to rapamycin in an Akt-dependent manner via p38 MAPK signaling. *Oncogene* 25: 6277–6290.
- Chrestensen CA, Schroeder MJ, Shabanowitz J, Hunt DF, Peló JW, et al. (2004) MK2 phosphorylates tristetraprolin on in vivo sites including S178, a site required for 14-3-3 binding. *J Biol Chem* 279: 10176–10184.
- Stoecklin G, Stubbs T, Kedersha N, Wax S, Rigby WF, et al. (2004) MK2-

- induced tristetraprolin:14-3-3 complexes prevent stress granule association and ARE-mRNA decay. *EMBO J* 23: 1313–1324.
49. Pozuelo Rubio M, Geraghty KM, Wong BH, Wood NT, Campbell DG, et al. (2004) 14-3-3-Affinity purification of over 200 human phosphoproteins reveals new links to regulation of cellular metabolism, proliferation and trafficking. *Biochem J* 379: 395–408.
 50. Ramaswamy S, Nakamura N, Vazquez F, Batt DB, Perera S, et al. (1999) Regulation of G1 progression by the PTEN tumor suppressor protein is linked to inhibition of the phosphatidylinositol 3-kinase/Akt pathway. *Proc Natl Acad Sci U S A* 96: 2110–2115.
 51. Riggs KJ, Saleque S, Wong KK, Merrell KT, Lee JS, et al. (1993) Yin-yang 1 activates the c-myc promoter. *Mol Cell Biol* 13: 7487–7495.
 52. Gherzi R, Russell DS, Taylor SI, Rosen OM (1987) Reevaluation of the evidence that an antibody to the insulin receptor is insulin mimetic without activating the protein tyrosine kinase activity of the receptor. *J Biol Chem* 262: 16900–16905.
 53. Gruhler A, Olsen JV, Mohammed S, Mortensen P, Faergeman NJ, et al. (2005) Quantitative phosphoproteomics applied to the yeast pheromone signaling pathway. *Mol Cell Proteomics* 4: 310–327.