The molecular scaffold kinase suppressor of Ras 1 is a modifier of Ras(V12)-induced and replicative senescence

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The Molecular Scaffold Kinase Suppressor of Ras 1 Is a Modifier of RasV12-Induced and Replicative Senescence

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In primary mouse embryo fibroblasts (MEFs), oncogenic Ras induces growth arrest via Raf/MEK/extracellular signal-regulated kinase (ERK)-mediated activation of the p19ARF/p53 and INK4/Rb tumor suppressor pathways. Ablation of these same pathways causes spontaneous immortalization in MEFs, and oncogenic transformation by Ras requires ablation of one or both of these pathways. We show that Kinase Suppressor of Ras 1 (KSR1), a molecular scaffold for the Raf/MEK/ERK cascade, is necessary for RasV12-induced senescence, and its disruption enhances primary MEF immortalization. RasV12 failed to induce p53, p19ARF, p16INK4a, and p15INK4b expression in KSR1−/− MEFs and increased proliferation instead of causing growth arrest. Reintroduction of wild-type KSR1, but not a mutated KSR1 construct unable to bind activated ERK, rescued RasV12-induced senescence. On continuous culture, deletion of KSR1 accelerated the establishment of spontaneously immortalized cultures and increased the proportion of cultures escaping replicative crisis. Despite enhancing escape from both RasV12-induced and replicative senescence, however, both primary and immortalized KSR1−/− MEFs are completely resistant to RasV12-induced transformation. These data show that escape from senescence is not necessarily a precursor for oncogenic transformation. Furthermore, these data indicate that KSR1 is a member of a unique class of proteins whose deletion blocks both senescence and transformation.

The Raf/MEK/extracellular signal-regulated kinase (ERK) cascade is one of several growth-regulatory pathways directly downstream of the small G-protein Ras. Ras was first identified as the transforming agent in Harvey murine sarcoma virus (63). Subsequent studies showed that mutations in Ras family members can lead to their constitutive activation, and these activated Ras proteins could be found in a variety of human cancers (3, 14, 51). In mammalian fibroblasts, activated Ras can cause either transformation or irreversible growth arrest, depending on the cellular context and the expression of cooperating oncogenes (11, 39, 59).

In primary murine fibroblasts, mutationally activated Ras (RasV12) leads to an irreversible growth arrest characterized by up-regulation of the tumor suppressor proteins p53 and p19ARF and the cyclin-dependent kinase inhibitor p16INK4a (50, 59). Primary cells arrested by activated Ras are phenotypically indistinguishable from those arrested by continuous culture (9, 27, 59). These cells have an enlarged, flattened morphology, stop proliferating at subconfluent cell densities, and express several markers of replicative senescence (59). In RasV12-expressing cells, inactivation of the p19ARF/p53 pathway, either genetically or by introduction of viral oncogenes that inactivate p53-mediated growth arrest, bypasses cellular senescence and leads to transformation (22, 34, 39, 50, 58, 59). While deletion of p16INK4a does not bypass RasV12-induced senescence in murine cells, disruption of p16INK4a in human cells allows for a bypass of RasV12-induced senescence (4, 6, 28, 29, 70). This could be due to both differences in regulation of the INK4a/ARF locus between mouse and human cells and the relative importance of different INK4 family members in mouse cells.

RasV12 induces expression of both p16INK4a and p19ARF in primary mouse fibroblasts (50, 59), but RasV12 cannot induce p14ARF expression in human fibroblasts (21, 69). Differences in regulation of the INK4a/ARF locus in human and mouse cells are not completely understood. p15INK4b, a related INK4 family member, is also regulated by RasV12 in mouse fibroblasts. p15INK4b is up-regulated by RasV12, and deletion of p15INK4b abrogated RasV12-induced senescence in primary mouse embryo fibroblasts (MEFs) (40, 43). These data indicate that members of the INK4 family of proteins are important regulators of RasV12-induced senescence in both mouse and human fibroblasts.

Expression of constitutively activated Raf, constitutively activated MEK, or Ras effector loop mutants that activate Raf has shown that both the senescence-promoting (20, 41, 76) and oncogenic (12, 24, 44, 54, 68, 71) properties of RasV12 can be replicated by activation of the Raf/MEK/ERK cascade. Expression of constitutively activated Raf or MEK in primary mouse or human fibroblasts causes cell cycle arrest, induction of p53 and p16INK4a, and expression of senescence-associated (SA) β-galactosidase activity (20, 41, 76). Growth arrest induced by the Raf/MEK/ERK cascade relies primarily upon p53 signaling. The ability of constitutively activated Raf to cause growth arrest is dependent upon its ability to induce expression of p21CIP1 (60, 72). Furthermore, Raf/MEK/ERK signaling...
stabilizes p53 expression and can regulate whether p53 activation produces senescence or apoptosis (20).

Kinase Suppressor of Ras 1 (KSR1) is a molecular scaffold for the Raf/MEK/ERK cascade (37, 46, 49). KSR1 expression regulates the intensity and duration of growth factor-induced ERK activation to modulate a cell’s proliferative, oncogenic, and adipogenic potential (36, 37, 55). Importantly, immortalized KSR1−/− MEFs are resistant to oncogenic transformation by RasV12, which can be rescued by ectopic expression of KSR1 (37). Deletion of KSR1 blocks RasV12-induced ERK activation but not activation of other Ras effector pathways, indicating that KSR1-scaffolded ERK activation is necessary for RasV12-induced transformation (37).

Given the necessity of KSR1 expression in RasV12-induced transformation in immortalized MEFs, we assessed whether KSR1 was necessary for RasV12-induced senescence in primary MEFs. RasV12-induced senescence and replicative senescence are phenotypically similar and require many of the same pathways. Therefore, we also assessed whether KSR1 could play a role in cellular immortalization. We show that KSR1 is necessary for RasV12-induced senescence and that its deletion accelerates 3T3-mediated immortalization of primary MEFs. KSR1−/− MEFs were resistant to RasV12-induced senescence and instead showed increased proliferation. Furthermore, RasV12 failed to induce p53, p19ARF, p16INK4a, and p15INK4b expression in primary KSR1−/− MEFs. Reintroduction of wild-type KSR1, but not a mutated KSR1 construct unable to bind activated ERK, restored RasV12-induced senescence. On continuous culture, deletion of KSR1 accelerated spontaneous immortalization and increased the number of primary cultures escaping replicative crisis. Coupled to the observation that immortalized KSR1−/− MEFs are resistant to RasV12-induced transformation (37, 42), these data demonstrate that KSR1-scaffolded ERK activity is necessary for RasV12-induced and replicative senescence and for transformation.

MATERIALS AND METHODS

Cell culture. Cells were maintained in Dulbecco's modified Eagle's medium supplemented with 10% fetal bovine serum, 2 mM L-glutamine, 0.1 mM minimal essential medium nonessential amino acids, 1% penicillin-streptomycin, and 55 μM β-mercaptoethanol. Cells were incubated at 37°C in 5% CO2. Construction and production of recombinant retroviruses. KSR1-FLAG, KSR1.C809Y-FLAG, and KSR1.FSFP/AAAP-FLAG were subcloned from the EcoRI and SalI sites of pCMV5 (33) into the EcoRI and XhoI sites of MSCV-IRES-GFP (67) until immortalized populations of cells emerged. To assess immortalization constructs, KSR1−/− MEFs were collected and filtered. Viral supernatants were then either stored at −80°C or used immediately to bind activated ERK, restored RasV12-induced senescence. On continuous culture, deletion of KSR1 accelerated spontaneous immortalization and increased the number of primary cultures escaping replicative crisis. Coupled to the observation that immortalized KSR1−/− MEFs are resistant to RasV12-induced transformation (37, 42), these data demonstrate that KSR1-scaffolded ERK activity is necessary for RasV12-induced and replicative senescence and for transformation.

RESULTS

KSR1 is necessary for RasV12-induced senescence. Expression of oncogenic Ras causes cellular senescence in primary MEFs via activation of the Raf/MEK/ERK cascade (9, 20, 41,
KSR1 is a molecular scaffold of the Raf/MEK/ERK cascade (37, 46, 49). Previous data indicated that KSR1 was necessary for RasV12 to transform immortalized MEFs (37). To assess whether KSR1 was required for Ras V12-induced senescence, early-passage KSR1+/−/+/− MEFS were infected with a recombinant retrovirus expressing Ras V12 or with control virus and were assessed for characteristics of senescence. As expected, expression of RasV12 in KSR1+/−/+/− MEFS induced cellular senescence. KSR1+/−/+/− MEFS expressing RasV12 failed to proliferate in culture (Fig. 1A), had a characteristic enlarged and flattened morphology (Fig. 1B), and demonstrated SAβ-galactosidase activity (Fig. 1C). In contrast, RasV12 did not induce growth arrest in KSR1+/+/+ MEFS but instead induced proliferation. KSR1+/−/+/− MEFS expressing RasV12 proliferated at a much higher rate than control MEFs in culture (Fig. 1A), were morphologically similar to control fibroblasts (Fig. 1B), and lacked β-galactosidase activity (Fig. 1C). Previous data demonstrate that, although Ras activa-
tion of the Raf/MEK/ERK effector pathway is defective in immortalized KSR1+/− MEFs, activation of other Ras effector pathways is unaltered (37). These data indicate that the KSR1-scaffolded Raf/MEK/ERK effector pathway is critical in determining whether RasV12 induces senescence or cell proliferation in primary MEFs.

RasV12 is reported to induce senescence in primary cells via the p19ARF/p53 and INK4/Rb pathways (1, 13, 15, 20, 21, 30, 43, 50, 52, 57, 59, 64, 76). To understand which of these pathways failed to be induced by RasV12 in KSR1+/− MEFs, Western blotting was performed for p53, PML, p21CIP1, p19ARF, DMP1, p16INK4a, and p15INK4b in KSR1+/− and KSR1+/- MEFs expressing RasV12 and in control cells. Western blot analyses for Ras, KSR1, tubulin, and actin were performed as controls. Retroviral introduction of RasV12 induced the phosphorylation of MEK and ERK and the expression of p19ARF was not induced by RasV12 in KSR1+/− MEFs, whereas supraphysiologic levels of KSR1 further enhance transformation and ERK activation, whereas supraphysiologic levels of KSR1+/− MEFs failed to be induced by RasV12 in KSR1+/− MEFs. In contrast, expression of RasV12 failed to stimulate the phosphorylation of MEK or ERK or to induce p53, PML, p21CIP1, p19ARF, DMP1, p16INK4a, or p15INK4b expression in KSR1+/− MEFs (Fig. 1D). Interestingly, although p19ARF was not induced by RasV12 in KSR1+/− MEFs, we routinely saw a two- to fourfold elevation in basal p19ARF in KSR1+/− MEFs compared to KSR1+/- MEFs (Fig. 1D, vector controls). Elevated p19ARF levels can indicate a lack of p53 function (34, 53). To assess whether KSR1+/− MEFs lacked functional p53, p53 induction and p53 activity in response to γ irradiation were assessed in early-passage KSR1+/− and KSR1+/- MEFs.

p53 was induced rapidly and transiently in both KSR1+/− and KSR1+/- MEFs (Fig. 2). To assess whether the induced p53 was transcriptionally active, Western blot analysis was performed for two transcriptional targets of p53, mdm2 and p21CIP1 (2, 18, 73). Both mdm2 and p21CIP1 were induced 2 to 4 h after exposure of KSR1+/− and KSR1+/- MEFs to γ irradiation (Fig. 2), indicating that p53 can be activated by ATM following DNA damage in KSR1+/− MEFs. These data demonstrate that KSR1+/− MEFs express functional p53 but that p53 activity cannot be induced by activated RasV12 to trigger cellular senescence in the absence of KSR1.

To address whether KSR1 was necessary for RasV12 to cause senescence in primary MEFs, KSR1 was reintroduced into KSR1+/− MEFs by use of a bicistronic retrovirus encoding KSR1 and green fluorescent protein (GFP). The level of KSR1 expression has significant effects on RasV12-mediated transformation and Raf/MEK/ERK signaling (37). Reintroduction of physiologic levels of KSR1 rescues RasV12-mediated transformation and ERK activation, whereas supraphysiologic levels of KSR1 further enhance transformation and ERK activation to a maximum at 14 times the level of KSR1 expression found in KSR1+/− MEFs (37). Higher levels of KSR1 expression inhibit transformation and ERK activation, consistent with the role of KSR1 as a molecular scaffold (8, 37). Therefore, cells expressing low levels of ectopic KSR1 were selected by flow cytometry to ensure that physiologically relevant levels of KSR1 expression, shown previously not to affect the rate of proliferation, were used in our analysis (Fig. 3D). Reintroduction of KSR1 restored RasV12-induced senescence in KSR1+/− MEFs (Fig. 3), as assessed by proliferative arrest (Fig. 3A) and SA β-galactosidase activity (Fig. 3B and C). KSR1 also restored RasV12-mediated induction of p53, PML, p21CIP1, p19ARF, DMP1, p16INK4a, and p15INK4b, lowered basal levels of p19ARF, and restored the responsiveness of p19ARF to RasV12 (Fig. 3D).

**Fig. 2.** Induction of p53 activity by γ irradiation is independent of KSR1. Passage 4 KSR1+/− and KSR1+/- MEFs were irradiated with 8 Gy, and whole-cell extracts were prepared at the indicated times after radiation exposure. Lysates were probed with the indicated antibodies to assess the induction of p53 activity. Actin was used to demonstrate equal loading of each sample. Data are representative of two independent experiments.

RasV12-induced senescence requires KSR1-ERK interaction. While the site(s) of association between KSR1 and Raf has not been well defined, sites of interaction for MEK and activated ERK have been identified on KSR1. Furthermore, site-directed mutagenesis of KSR1 can abrogate the KSR1-MEK or KSR1-ERK interactions. Mutated forms of KSR1 can be used to assess the relative role each KSR1-effector interaction plays in KSR1-mediated biological functions (5, 19, 31, 47, 65, 75). To assess the effects of KSR1-scaffolded ERK activation on RasV12-induced senescence, mutated KSR1 constructs lacking the ability to interact with MEK (KSR1.C809Y) (47, 65, 75) or activated ERK (KSR1.FSFP/AAAP) (19, 31) were introduced into KSR1+/− MEFs expressing RasV12 or control vector by use of the bicistronic retroviral system described above. Introduction of these mutated KSR1 constructs into RasV12-expressing KSR1+/− MEFs demonstrated that the KSR1-ERK interaction, but not the KSR1-MEK interaction, was necessary for RasV12 to induce senescence. KSR1.C809Y, a mutated KSR1 construct unable to bind MEK (47, 65, 75), was able to induce growth arrest and SA β-galactosidase activity as well as wild-type KSR1 (Fig. 3A to C). In contrast, KSR1.FSFP/AAAP, a mutated form of KSR1 unable to bind activated ERK (19, 31), did not arrest growth and showed a diminished ability to promote RasV12-induced SA β-galactosidase activity. KSR1.FSFP/AAAP cells expressing RasV12 did not, however, proliferate at rates as high as control (GFP) cells expressing RasV12, indicating that there may be a reduction in proliferative signals from RasV12 in the absence of an intact KSR1-ERK interaction (Fig. 3A-C).

Similarly, to KSR1+/− MEFs expressing wild-type KSR1, RasV12-induced expression of p53, p19ARF, DMP1, p16INK4a, and p15INK4b in KSR1+/− MEFs expressing KSR1.C809Y, providing further evidence that the KSR1-MEK interaction is dispensable during RasV12-induced senescence. In contrast, RasV12 induced expression of p53 and p19ARF, but
FIG. 3. The KSR1-ERK interaction is required, but the KSR1-MEK interaction is dispensable, for RasV12-induced senescence in KSR1−/− MEFs. Passage 5 KSR1−/− MEFs were infected with recombinant retrovirus encoding KSR1, a KSR1 construct unable to bind activated ERK (KSR1.FSFP/AAAP) or a KSR1 construct unable to bind MEK (KSR1.C809Y), and RasV12 or a control virus. Low levels of KSR1 expression were selected by FACS analysis for levels of GFP expression previously shown to correlate with 1× to 5× KSR1−/− levels. (A) Proliferation in passage 5 KSR1−/− MEFs expressing the indicated KSR1 construct and RasV12 (closed squares) or control (open diamonds) vectors. Separate duplicate dishes were assessed for cell number every 48 h on a Beckman Coulter Counter. Data are expressed as means ± SD of three independent experiments. (B) Photomicrographs (10×) of cells analyzed in panel A and stained to visualize SA-β-galactosidase activity as described in Materials and Methods. (C) Quantification of cells analyzed in panel A and stained to visualize SA-β-galactosidase (β-Gal) activity as described in Materials.
not p16INK4a or p15INK4b, in KSR1−/− MEFs expressing KSR1.FSFP/AAAP (Fig. 3D). Induction of p21CIP1 also required the interaction of KSR1 with ERK (Fig. 3D). This observation appears consistent with the p53-independent induction of p21CIP1 by Raf (72). RasV12-induced MEK phosphorylation is rescued by the expression of either KSR1.FSFP/AAAP or KSR1.C809Y. However, ERK activation is not rescued by KSR1.FSFP/AAAP (Fig. 3D). These data indicate that KSR1 is necessary for RasV12-induced senescence and that the effects of KSR1 require its interaction with activated ERK.

The effects of the FSFP/AAAP and C809Y mutations in KSR1 on RasV12-induced senescence led us to assess whether the KSR1-MEK or KSR1-ERK interactions were required for RasV12-mediated transformation in immortal MEFs. As observed previously (37), KSR1 expression was necessary for RasV12-induced transformation in immortalized KSR1−/− MEFs (Fig. 4A). The KSR1-MEK interaction was dispensable for transformation, as KSR1.C809Y cells expressing RasV12 showed enhanced colony formation in comparison to wild-type KSR1 cells. KSR1−/− MEFs expressing KSR1.FSFP/AAAP were also transformed. However, disruption of the interaction of KSR1 with activated ERK diminished the transforming potential of RasV12, as these cells showed only 30% of the colonies seen with cells expressing wild-type KSR1 (Fig. 4A).

Given the contrasting results observed upon disruption of KSR1-MEK and KSR1-ERK interactions, we sought to further understand the signaling properties of cells expressing these mutated KSR1 constructs. We examined the kinetics of PDGF-induced ERK activation in immortal KSR1−/− MEFs expressing KSR1, KSR1.C809Y, or KSR1.FSFP/AAAP (Fig. 4B). Cells expressing wild-type KSR1 showed rapid induction of ERK activation at 5 min, followed by a lower level of sustained signaling out to 2 h. When the KSR1-MEK interaction was disrupted by the C809Y mutation in KSR1, there was no decrease in peak ERK activation, and ERK phosphorylation was sustained in comparison to that of cells expressing wild-type KSR1. In contrast, disruption of the interaction of KSR1 with activated ERK (FSFP/AAAP) blunted peak ERK activation (Fig. 4B). These results suggest that the role of KSR1 is not only to facilitate activation of the Raf/MEK/ERK cascade but that KSR1 is also required to maintain the fidelity of RasV12-induced ERK activity necessary for senescence (Fig. 3) and transformation (Fig. 4).

**KSR1 enhances the cellular response to activated MEK.** Whereas previous studies have shown a role for KSR1 in facilitating the activation of Raf by Ras (45) and MEK by Raf (48, 49, 56), our data suggest that KSR1 promotes signal propagation downstream of MEK. To explore the role of KSR1 in facilitating signaling downstream of MEK, we examined cell transformation (Fig. 5) and senescence (Fig. 6) induced by a

Fig. 4. The KSR1-ERK interaction is required, but the KSR1-MEK interaction is dispensable, for RasV12-induced transformation and PDGF-induced ERK activation in immortal KSR1−/− MEFs. Immortal KSR1−/− MEFs were infected with recombinant retrovirus encoding KSR1, KSR1.FSFP/AAAP, or KSR1.C809Y and RasV12 or a control virus. Low levels of KSR1 expression were selected by FACS analysis for levels of GFP expression previously shown to correlate with 1/3 to 5/3 KSR1 levels. (A) Cells were assessed for transformation by growth on soft agar as described in Materials and Methods. Data are expressed as means ± SD from two independent experiments. (B) Triplicate wells expressing the indicated KSR1 construct were treated with 25 ng of PDGF/ml for the indicated times, and ERK1/2 phosphorylation levels were determined by in-cell Western blotting for ERK1 and pERK1/2 with a Li-Cor Odyssey system. Data are expressed as ratios of pERK1/2 to ERK1. Data are expressed as means ± SD.

and Methods. Separate triplicate dishes were quantified for each cell line, with a minimum of 50 cells quantified per well. Data are expressed as mean percentages of cells ± SD from three independent experiments. (D) Western blot analysis of whole-cell extracts prepared from passage 5 KSR1−/− MEFs expressing the indicated KSR1 constructs and RasV12 or control vector. Lysates were probed with the indicated antibodies to detect induction and activation of each protein by RasV12. Actin and tubulin were used to demonstrate equal loading of each sample, and Ras and KSR1 expression results are shown as controls. Data are representative of four independent experiments.
constitutively active MEK construct (MEKEE) containing glutamic acid substitutions for Ser218/222 (7, 12, 41, 44) in the presence and absence of KSR1. To study transformation, immortal KSR1/−/− and KSR1/+/+ MEFs were infected with recombinant retrovirus encoding MEKEE, RasV12, or a control virus. (A) Western blot analysis of whole-cell extracts prepared from immortal KSR1/−/− and KSR1/+/+ MEFs expressing MEKEE, RasV12, or control vector. Lysates were probed with antibodies against pERK1/2 and ERK1/2 to detect activation of ERK by MEKEE or RasV12. Actin was used to demonstrate equal loading of each sample, and expression blots of Ras, MEK1, and KSR1 are shown as controls. For MEK1 blots, low exposures are shown to indicate cells that have received the MEKEE transgene and not expression of endogenous MEK1. Data are representative of four independent experiments. (B and C) Cells were assessed for transformation by growth on soft agar (B) and focus formation (C) as described in Materials and Methods. Data are expressed as means ± SD from two independent experiments.

FIG. 5. KSR1 is not required for, but enhances, MEKEE-induced transformation in immortal KSR1/−/− MEFs. Immortal KSR1/−/− and KSR1/+/+ MEFs were infected with recombinant retrovirus encoding MEKEE, RasV12, or a control virus. (A) Western blot analysis of whole-cell extracts prepared from immortal KSR1/−/− and KSR1/+/+ MEFs expressing MEKEE, RasV12, or control vector. Lysates were probed with antibodies against pERK1/2 and ERK1/2 to detect activation of ERK by MEKEE or RasV12. Actin was used to demonstrate equal loading of each sample, and expression blots of Ras, MEK1, and KSR1 are shown as controls. For MEK1 blots, low exposures are shown to indicate cells that have received the MEKEE transgene and not expression of endogenous MEK1. Data are representative of four independent experiments. (B and C) Cells were assessed for transformation by growth on soft agar (B) and focus formation (C) as described in Materials and Methods. Data are expressed as means ± SD from two independent experiments.

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extent than seen in KSR1<sup>−/−</sup> MEFs. When grown on a semi-solid medium, KSR1<sup>−/−</sup> MEFs expressing MEKEE formed approximately 25% of the colonies seen in KSR1<sup>+/+</sup> MEFs and when contact inhibition was assessed required 5 to 6 weeks to form colonies equal in size to those observed 10 days after plating KSR1<sup>+/+</sup> MEFs expressing MEKEE.

MEKEE also caused cellular senescence in primary KSR1<sup>+/+</sup> MEFs (Fig. 6). However, as observed with trans-
formation, MEKEE caused an intermediate phenotype in primary KSR1+/− MEFs. Expression of MEKEE caused a modest increase in ERK activation but failed to induce expression of p53 or the INK4 proteins (Fig. 6A). Furthermore, primary KSR1+/− MEFs expressing MEKEE did not undergo growth arrest, instead proliferating as well as or better than control cells (Fig. 6B). When stained for β-galactosidase activity, primary KSR1+/− MEFs expressing MEKEE consistently showed 35 to 40% positive staining (versus 75 to 80% for KSR1+/+ MEFs expressing MEKEE or RasV12) (Fig. 6B and C). These data demonstrate that, similarly to its effects on transformation (Fig. 5), MEKEE cannot fully promote senescence in the absence of KSR1. These data suggest that KSR1 promotes not only the activation of MEK (48) but also transmission of the activated MEK signal to its downstream target.

Deletion of KSR1 enhances spontaneous immortalization of fibroblasts. RasV12-induced senescence and replicative senescence are both mediated, in part, by activation of the p16INK4a/Rb pathways (50, 59). Since KSR1+/− MEFs were defective in RasV12-mediated induction of p53, p16INK4a, and p15INK4b and in RasV12-induced senescence, we assessed whether KSR1+/− MEFs would exhibit a propensity to escape replicative senescence. To assess whether KSR was involved in spontaneous immortalization of fibroblasts, KSR1+/− and KSR1+/+ MEFs were passaged by a 3T9 protocol (10, 67) until either cell death or spontaneous immortalization occurred. KSR1+/+ MEFs showed a rapid decline in cellular proliferation beyond passage 5 and exhibited marked amounts of cell death around passages 15 to 20, consistent with previous reports (Fig. 7A) (42). KSR1+/− MEFs also exhibited a rapid decline in cellular proliferation after passage 5 and were similar to KSR1+/+ MEFs in both appearance and number until approximately passage 15. At this point, KSR1+/− MEFs showed a brief proliferative burst (2 to 4 passages) followed by a second period of growth arrest which lasted 5 to 7 more passages. Between passages 23 and 26, KSR1+/− MEFs began to proliferate, and 10 out of 11 (91%) KSR1+/− cultures had immortalized by passage 30. In contrast, KSR1+/+ MEFs showed no signs of proliferation until passage 35 or later, after which 4 out of 11 (36%) KSR1+/+ cultures began to proliferate and eventually became immortal (Fig. 7A).

To assess the growth characteristics of KSR1−/− and KSR1+/+ MEFs during the immortalization process, cells from three independent KSR1−/− and KSR1+/+ cultures at passages 5, 10, 15, and 18 were assessed for proliferation rate at low density (Fig. 7B). Consistent with previously published data, early-passage KSR1−/− MEFs proliferated at a slightly slower rate than KSR1+/+ MEFs (42). However, we did not see the marked differences in proliferative rate between KSR1−/− and KSR1+/+ MEFs observed by Lozano et al. (42). The discrepancy might be explained by differences in passage number between the two experiments (see Discussion). When plated at passage 10, there was no difference in proliferative rate between KSR1−/− and KSR1+/+ MEFs for the first 6 days of the experiment. We observed increased cell proliferation in KSR1−/− MEFs between days 7 and 10 of this experiment, however, indicating that immortalized cells may already exist within the KSR1−/− cultures at this time. KSR1−/− MEFs plated at passages 15 and 18 also showed enhanced cellular proliferation compared to KSR1+/+ MEFs, with similar lag times of 6 to 8 days before the enhanced cell proliferation was observed (Fig. 7B). These data indicate that compared to KSR1+/+ MEFs, KSR1−/− MEFs are predisposed to spontaneous immortalization. Furthermore, these data show that im-
mortalized KSR1−/− MEFs exist in cultured cell populations as early as passage 10. The effect of KSR1 on the potential of MEFs to immortalize was tested further by plating KSR1+/+, KSR1−/−, and KSR1−/− MEFs at passage 9 at low density and allowing the cells to grow for 4 weeks. Analysis of the colonies formed from cells of each genotype (Fig. 7C) revealed that twice as many colonies arose from KSR1−/− MEFs at passage 9 as from KSR1+/+ MEFs. An intermediate number of colonies arose from MEFs heterozygous for KSR1. These data suggest that KSR1 serves as a barrier against immortalization.

**DISCUSSION**

Here we show that the molecular scaffold KSR1 is a potent modifier of replicative senescence. Deletion of KSR1 enhanced spontaneous immortalization of primary MEFs, increasing the frequency of immortalization and decreasing the time necessary for primary cultures to escape from replicative crisis. KSR1 was also required for senescence induced by activated RasV12. In the absence of KSR1, RasV12 stimulated proliferation instead of senescence. Expression of mutated forms of KSR1 revealed that the KSR1-ERK interaction was necessary for RasV12 to cause growth arrest of primary cells. Though the interaction of KSR1 with MEK was not required for RasV12-induced senescence, KSR1 expression amplified the effect of an activated MEK construct on senescence in primary MEFs and transformation in immortal MEFs. Signaling from RasV12 to both the p19ARF/p53 and INK4/Rb pathways was defective in KSR1−/− MEFs, which likely underlies both the escape from RasV12-induced senescence and the enhanced spontaneous immortalization observed in KSR1−/− MEFs.

RasV12 causes senescence by engaging the p19ARF/p53 and p16INK4a/Rb pathways, although the relative contributions of these pathways differ between mouse and human cells. p19ARF plays a more important role in senescence in mouse cells, whereas p16INK4a is more important in senescence in human cells (9, 28, 29, 50, 58, 59, 69). In murine fibroblasts, ablation of these pathways allows RasV12 to enhance cell proliferation instead of growth arrest (13, 34, 50, 52, 57, 59). KSR1 was necessary for RasV12 to increase phosphorylation of ERK and for the expression of p53, PML, p19ARF, DMP1, p16INK4a, and p15INK4b (Fig. 1D). In the absence of these antiproliferative signals, RasV12 caused proliferation instead of growth arrest in primary MEFs. RasV12 signals to the proliferative machinery via multiple effector pathways, including the PI3 kinase/Akt, RalGEF/Ral, and Raf/MEK/ERK cascades (23, 24). In primary murine cultures, activation of the Raf/MEK/ERK cascade, but not the other effector pathways, engages the p53/ARF and INK4/Rb pathways, causing senescence instead of proliferation (41, 76). Deletion of the molecular scaffold KSR1 blocks the ability of RasV12 to signal through the Raf/MEK/ERK effector pathway to these antiproliferative pathways (Fig. 1) but leaves signaling to other Ras effectors intact (37). Thus, in primary MEFs lacking KSR1, RasV12 signaling through the Raf/MEK/ERK signaling cassette to the antiproliferative p53/ARF and INK4/Rb pathways is limited, allowing proliferation instead of growth arrest.

The interaction of KSR1 with activated ERK appears necessary for RasV12-induced senescence (Fig. 5) and for maximal RasV12-induced transformation (Fig. 6). While the activation of MEK is intact in cells expressing KSR1.FSFP/AAAP, maximal ERK activation is lost; indicating that the interaction of KSR1 with activated ERK is necessary for signal fidelity. Interestingly, MEK activation is increased in KSR1−/− MEFs expressing KSR1.FSFP/AAAP, raising the possibility that a molecular brake on Raf activity is lost by disruption of KSR1 interaction with ERK. Dougherty et al. (17) recently reported feedback inhibition of Raf by ERK. Since MEK phosphorylation (and therefore Raf activity) is increased in KSR1.FSFP/AAAP cells, these data suggest that KSR1 may be required not only to facilitate but also to moderate signaling through the Raf/MEK/ERK cascade.

To assess whether KSR1 facilitates the activation of ERK by MEK, we examined the role of MEKEE (activated MEK) in senescence and transformation in KSR1−/− MEFs. We observed that the introduction of MEKEE into KSR1−/− MEFs yields a phenotype intermediate between those observed after introduction of RasV12 in KSR1+/+ and in KSR1−/− MEFs. While MEKEE transforms KSR1−/− MEFs, these cells have only 20% of the transformed foci compared to the results seen with KSR1+/− MEFs expressing MEKEE (Fig. 5). Additionally, while MEKEE does not cause growth arrest in primary KSR1−/− MEFs, there are an increased number of β-galactosidase-positive cells (Fig. 6). These data show that activated MEK is not sufficient to compensate for the lack of KSR1, indicating that KSR1 facilitates MEK function. These data reveal a previously unappreciated role of KSR1 in the maintenance of the fidelity of signaling from MEK to ERK. Furthermore, in conjunction with the intermediate phenotype seen with disruption of the interaction between KSR1 and activated ERK (FSFP/AAAP), these data show that specific scaffold-effector interactions are necessary to maintain signaling fidelity and assure the correct cellular response to pathway activation.

Expression of KSR1.C809Y, a form of KSR1 that cannot bind MEK (47, 65), still allowed RasV12 to induce MEK and ERK activation, senescence in primary MEFs, and transformation in immortal MEFs (Fig. 3 and 4). The C809Y mutation is orthologous to a loss-of-function mutation in KSR1 detected in genetic screenings using Caenorhabditis elegans (66). While others have shown that this mutation precludes MEK activation (56), we found that MEK and ERK phosphorylation are enhanced (Fig. 3). These differences may be due, in part, to differences in experimental design or in signaling between mammalian and invertebrate systems. The KSR1-MEK interaction is necessary for many KSR1 functions, including its ability to translocate to the nucleus (5) and promote PC12 cell differentiation (47). In these studies, KSR1.C809Y exhibited a clear loss of function, which validates the biological importance of the KSR1-MEK interaction. Others have also reported a lack of biological activity for KSR1.C809Y (32, 65), but these studies used a KSR1 overexpression system where the readout was pathway inactivation via combinatorial inhibition. We also found a lack of combinatorial inhibition by use of the KSR1.C809Y construct (unpublished data). However, loss of the KSR1-MEK interaction enhances pathway activity at physiologic levels (Fig. 3 and 4). The disruption of KSR1’s interaction with MEK may impair function in certain biological...
contexts (5, 47, 66) but increase function in others (Fig. 3 and 4) due to its ability to moderate signal output through the Raf/MEK/ERK signaling cassette. Elevating KSR1 expression promoted maximal activation of the Raf/MEK/ERK cascade, cell proliferation, and RasV12-induced transformation (37). However, ERK activation must be constrained within a narrow range by physiological levels of KSR1 to limit proliferative signals and promote adipogenesis (36, 37). Therefore, KSR1 may be required to interact with MEK and moderate its activity when a biological effect requires restrained ERK activation (e.g., during differentiation). These data indicate that specific KSR1-effector interactions are key regulators of a cell’s replicative potential.

KSR1−/− MEFs immortalize more readily than KSR1+/+ MEFs (Fig. 7). These data are reminiscent of the targeted disruption of p16INK4a. While disruption of p16INK4a does not immediately immortalize MEFs, knockdown of p16INK4a levels using antisense RNA constructs accelerates the establishment of immortalized cell lines (10). Furthermore, a greater proportion of p16INK4a−/− cultures immortalize compared to wild-type cell results (61, 62). We observed that disruption of KSR1 prevented p16INK4a expression by RasV12. Thus, a deficit in p16INK4a/Rb pathway regulation may be a central contributor to the accelerated immortalization of KSR1−/− MEFs.

While we observed only a slight difference in the low-density proliferative rate between KSR1−/− and KSR1+/+ MEFs at passage 5 (Fig. 7B), Lozano et al. reported a 50% reduction in the proliferative rate of early-passage KSR1−/− MEFs (42). Their studies, however, were conducted at a population doubling of <6, which corresponds to our MEFs at passages 1 to 3. Although we have not conducted low-density proliferative studies at these early passages, our data are consistent with low-passage-number KSR1−/− MEFs showing decreased cell proliferation compared to KSR1+/+ MEFs. When low-density proliferative studies were seeded at passage 10, 15, or 18, however, we observed increased proliferation in KSR1−/− MEFs beginning around day 7 (Fig. 7B). These data would indicate that KSR1−/− MEF cultures at passages 10, 15, and 18 already contain immortal cells, which are detectable when the MEFs were allowed to grow at a low density.

Premature senescence has been proposed as a tumor-suppressive mechanism, and escape from cellular senescence is one of several events which predispose cells toward oncogenic transformation (9). These data suggest that KSR1 might function to limit tumor susceptibility, since its deletion impedes cellular senescence. Furthermore, an inefficient senescence response resulting from disruption of KSR1 might facilitate tumor progression induced by oncogenic mutations that are not dependent upon Ras regulation of the Raf/MEK/ERK cascade. However, when assessing the transforming potential of RasV12 in KSR1−/− MEFs, we and others have found that KSR1 is necessary for RasV12-mediated transformation in both primary (42) and immortal (37) MEFs, indicating that KSR1 is a positive modifier of tumorigenesis. This ostensible dual role for KSR1 may result from its function as a molecular scaffold for the Raf/MEK/ERK cascade. Signaling through the Raf/MEK/ERK cascade moderates cell fate decisions depending upon cellular context. Control of signal output through molecular scaffolds has been proposed as one of several nodes directing cell fate (35, 36). In both primary and immortal MEFs, KSR1 expression moderates ERK activity to affect a cell fate (Fig. 1 and references 36 and 37), with the biologic outcome dependent upon cellular context and the overall activation of downstream effectors.

These data suggest that, in some circumstances, escape from premature senescence may not be an inextricable step toward cell transformation and tumorigenesis. Senescent fibroblasts, when seeded as tumor stroma, can promote epithelial cell transformation in situ and tumorigenesis in vivo (9, 38). Senescent fibroblasts secrete both soluble factors and extracellular matrices that promote the growth of premalignant, but not normal, epithelial cells. Furthermore, this ability to promote tumorigenesis occurs irrespective of whether the senescence was induced by replicative exhaustion or oncogenic RasV12 (9, 38). Since KSR1−/− MEFs are resistant to RasV12-induced senescence (Fig. 1) and less susceptible to replicative senescence (Fig. 7), it is conceivable that targeted disruption of KSR1 function could not only block the transforming capacity of cancer cells but also diminish the ability of stromal cells to promote tumorigenesis. Xing et al. (74) recently reported that treatment of EGFR-A431 or PANC-1 cells with antisense oligonucleotides against KSR1 blocked their proliferation in situ and in immunodeficient mice. Furthermore, the authors showed that treatment of mice with antisense oligonucleotides against KSR1 reduced the volume of established PANC-1 tumors. Based on these findings, Xing et al. (74) proposed phase 1 clinical trials to assess inactivation of KSR1 in pancreatic cancers. Our data suggest that the targeted disruption of KSR1 by use of antisense oligonucleotides could have therapeutic efficacy against RasV12-driven cancers at multiple levels. Within the tumor cells, reduction of KSR1 expression should reduce proliferative signals. In surrounding tissues, reduction of KSR1 expression could decrease the formation of senescent cells, thereby reducing the tumor-promoting properties of the surrounding stroma.

Based on these data, we propose that KSR1 expression is a barrier that cells must overcome during immortalization. While spontaneous deletion of KSR1 to escape senescence has not been reported, disruption of KSR1-regulated pathways would have the same effect. KSR1 allows RasV12 to engage the antiproliferative p19ARF/p53 and INK4/Rb pathways. Spontaneous mutations within these pathways promote immortalization (25, 34). Furthermore, genetic inactivation of either of these pathways blocks both RasV12-induced and replicative senescence (1, 10, 13, 20, 26, 30, 34, 50, 52, 57–59). The inability of RasV12 to induce senescence in KSR1−/− MEFs, combined with the enhanced propensity of KSR1−/− MEFs to immortalize, indicates that KSR1 is a potent modifier of replicative potential.

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