Somatic p16INK4a Loss Accelerates Melanomagenesis

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Somatic p16^{INK4a} loss accelerates melanomagenesis

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Introduction

Melanoma, the most lethal form of skin cancer, is increasing in incidence and mortality in the United States (Chin et al., 2006). Alterations of three genetic pathways characterize the majority of melanomas: activation of the RAS–RAF–extracellular signal-regulated kinase (ERK) pathway, inactivation of the p16^{INK4a}–CDK4–retinoblastoma (RB) pathway and inactivation of the alternate open reading frame (ARF)–murine double minute 2–p53 pathway. The RAS–RAF–ERK pathway is a mitogen-activated kinase cascade, which induces diverse transcriptional changes associated with increased proliferation, survival, motility and immune surveillance (Pearson et al., 2000; Johansson et al., 2007; Petermann et al., 2007; Shields et al., 2007). Per the Compilation of Somatic Mutations in Cancer (COSMIC, see (Forbes et al., 2006)), activating mutations of N-RAS occur in 21% of melanomas, those of K-RAS in 2% and of B-RAF in 44%, and these lesions seem to be mutually exclusive, consistent with an epistatic relationship. The presence of activating B-RAF mutations in a high proportion of dysplastic nevi indicates that aberrant activation of the RAS–RAF pathway is not sufficient for tumorigenesis and that additional genetic lesions are required to effect malignant transformation (Davies et al., 2002). Strong RAS–RAF activation has been shown to induce p16^{INK4a} expression and ‘oncogene-induced senescence’ in vitro and in vivo (Serrano et al., 1997; Zhu et al., 1998; Michaloglou et al., 2005), providing a tumor biological basis for cooperative interactions between p16^{INK4a} extinction and RAS–RAF activation.

The INK4/ARF (CDKN2a/b) locus at 9p21 encodes three distinct tumor suppressor proteins—p15^{INK4b}, p16^{INK4a} and ARF. A significant body of human and murine genetic data have determined that p16^{INK4a} and ARF have an important role in melanoma suppression (reviewed in (Kim and Sharpless, 2006)), whereas the role of p15^{INK4b} in this disease is less clear. INK4a/ARF deletion occurs in 50% of human melanomas, making it the most common site of genomic loss in melanomas (Curtin et al., 2005), with homozygous deletion being relatively common (Grafstrom et al., 2005). ARF blocks murine double minute 2-induced degradation of p53, whereas p16^{INK4a} and p15^{INK4b} inhibit cyclin-dependent kinases 4 and 6, leading to RB-hypophosphorylation and cell cycle arrest. Although ARF loss is the most common lesion of the ARF–murine double minute 2–p53 pathway in melanoma, mutational inactivation of p53 is observed in 10–30% of melanomas (Albino et al., 1994; Sparrow et al., 1995; Akslen et al., 1998; Zerp et al., 1999).

Several genetically engineered mouse models of melanoma using constitutively active and inducible transgenes and germline knockout alleles have studied

Loss of p16^{INK4a}–RB and ARF–p53 tumor suppressor pathways, as well as activation of RAS–RAF signaling, is seen in a majority of human melanomas. Although heterozygous germline mutations of p16^{INK4a} are associated with familial melanoma, most melanomas result from somatic genetic events: often p16^{INK4a} loss and N-RAS or B-RAF mutational activation, with a minority possessing alternative genetic alterations such as activating mutations in K-RAS and/or p53 inactivation. To generate a murine model of melanoma featuring some of these somatic genetic events, we engineered a novel conditional p16^{INK4a}-null allele and combined this allele with a melanocyte-specific, inducible CRE recombinase strain, a conditional p53-null allele and a loxP-stop-loxP activatable oncogenic K-Ras allele. We found potent synergy between melanocyte-specific activation of K-Ras and loss of p16^{INK4a} and/or p53 in melanomagenesis. Mice harboring melanocyte-specific activated K-Ras and loss of p16^{INK4a} and/or p53 developed invasive, unpigmented and nonmetastatic melanomas with short latency and high penetrance. In addition, the capacity of these somatic genetic events to rapidly induce melanomas in adult mice suggests that melanocytes remain susceptible to transformation throughout adulthood.

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the interaction of Ras activation and p16\textsuperscript{Ink4a}/Arf/p53 loss. Mice engineered with a constitutive, melanocyte-specific, mutant H-Ras transgenic allele on an Ink4a/Arf-deficient background (Tyr\textsuperscript{Ras} Ink4a/Arf \textbar{\textdash} ) were shown to develop melanoma with high penetrance and short latency (Chin et al., 1997). Using a doxycycline-inducible mutant H-Ras allele on an Ink4a/Arf-deficient background, it was determined that persistent activation of H-Ras is required for both melanoma initiation and maintenance, thus establishing the concept of tumor maintenance (Chin et al., 1999). Melanocyte-specific expression of an activated N-Ras transgene in an Ink4a/Arf-deficient background can also generate melanomas that can metastasize to the lymph nodes, lung and liver (Ackermann et al., 2005). A role for p53 in melanoma was substantiated in Tyr\textsuperscript{Ras} transgenic mice that were mutant for p53, which develop melanomas that retain strong p16\textsuperscript{INK4a} expression (Bardeesy et al., 2001). It is noteworthy and of relevance to this study that the Tyr\textsuperscript{Ras} transgene on a germline p16\textsuperscript{INK4a}-null background exhibited a weaker melanoma phenotype when compared with the Tyr\textsuperscript{Ras} transgene on either a germline Arf or p53-null background (Bardeesy et al., 2001; Kannan et al., 2003). This murine observation is curious in light of the prominent role of p16\textsuperscript{INK4a} extinction in human melanomas, raising the possibility of cross-species differences in the rate-limiting role of this key RB pathway component and/or of the fact that germline vs somatic inactivation of p16\textsuperscript{INK4a} is a critical parameter of its impact on melanocyte biology.

In aggregate, these genetic studies have clearly established the cooperation of Ras activation and Arf/p53 inactivation in melanomagenesis, but have suggested a more modest role for p16\textsuperscript{INK4a} loss in driving melanoma development in the mouse. This modest impact of p16\textsuperscript{INK4a} loss seems to contrast with the prominent role of p16\textsuperscript{INK4a} in human melanoma, as reflected by the robust melanoma-prone condition in the setting of germline or somatic p16\textsuperscript{INK4a} mutations that spare Arf or p15\textsuperscript{INK4c} in many cases (FitzGerald et al., 1996; Smith-Sorensen and Hovig, 1996; Walker et al., 1998; Daniotti et al., 2004). It is important to note that a few cases of ARF germline or somatic mutations that spare p16\textsuperscript{INK4a} have been identified, suggesting that both products of the INK4a/ARF locus have independent tumor suppressor activity in melanoma (Rizos et al., 2001; Hewitt et al., 2002). Several possible explanations for the apparent cross-species differences have been suggested, including differences in the anticaner potency of p16\textsuperscript{INK4a} vs ARF between mouse and man (Gil and Peters, 2006; Evan and d’Adda di Fagagna, 2009), bias derived from studies using transgene-driven overexpression of activated Ras (Tuveson et al., 2004), as well as epigenetic compensation in mouse germline null for p16\textsuperscript{INK4a}. With regard to the latter possibility, germline p16\textsuperscript{INK4a} inactivation is associated with increased, presumably compensatory, expression of other negative regulators of the cell cycle, such as p15\textsuperscript{INK4b} and p18\textsuperscript{INK4c} (Krimpenfort et al., 2007; Ramsey et al., 2007; Wiedemeyer et al., 2008). Furthermore, somatic loss of p16\textsuperscript{INK4a} and melanoma

**Results**

To determine the effect of somatic loss of p16\textsuperscript{INK4a} and/or p53 and activation of oncogenic K-Ras, we used an established 4-hydroxytamoxifen (4-OHT)-inducible melanocyte-specific CRE allele (Tyr-CRE-\textsuperscript{ER}\textsuperscript{2} (Bosenberg et al., 2006)), together with conditional alleles such as Lox-Stop-Lox-KRas\textsuperscript{G12D} (Johnson et al., 2001), a floxed p53-null allele (p53\textsuperscript{flox}) (Jonkers et al., 2001) and a newly generated floxed p16\textsuperscript{INK4a}-null allele (p16\textsuperscript{B}). In a subset of mice, CRE recombination was confirmed using a \(\beta\)-galactosidase reporter allele that, on Cre-mediated excision of a Lox-Stop-Lox cassette, expresses the enzyme; it was observed that cells stain positively in the \(\beta\)-galactosidase assay (Rosa26-LSL-\(\beta\)-galactosidase, Soriano, 1999) (Supplementary Figure 1). The p16\textsuperscript{B} allele was generated by inserting LoxP elements \(\sim 3.5\) kb 5’ to exon 1z and immediately 3’ to the p16\textsuperscript{INK4a} exon 1z (Supplementary Figure 2a, see also Supplementary Methods). The 5’ LoxP element was placed in a variable
number of tandem repeat region that is not conserved between 129SvJ and C57Bl/6 strains, and therefore not likely to be a critical Ink4a/Arf regulator. Correct targeting of the locus was confirmed by Southern blotting, PCR and sequencing (Supplementary Figure 2b and c). CRE expression in p16L/L murine embryo fibroblasts and melanocytes demonstrated selective p16INK4a exon 1α excision, loss of p16 INK4a protein expression (Supplementary Figure 3a and c) without an alteration in Arf expression (Supplementary Figure 3b and c). In contrast to deletion of Arf or p53, excision of p16INK4a with or without concomitant K-Ras activation did not enhance melanocyte growth in vitro (Supplementary Figure 3d).

Intercrosses produced the Tyr-CRE-ERT2+/KRasLSL+/p16INK4a+/p53L/L experimental cohort (TKp16L/Lp53L/L), as well as indicated control cohorts. TKp16L/L micemice and control litters were topically treated as neonates with 4-OHT to activate CRE and induce recombination in melanocytes as previously described (Bosenberg et al., 2006; see schematic in Supplementary Figure 1). Within 14 weeks, all 4-OHT-treated TKp16L/Lp53L/L mice developed aggressive tumors and hence had to be killed (Figure 1a, Table 1). Nonmelanoma tumors were not observed in 4-OHT-treated TKp16L+/p53L/L mice (n = 15) (Table 1). In contrast, only 1 of 14 of the 4-OHT-treated TKp16L/p53L+/+ mice developed melanoma at 60 weeks post treatment (Table 1). PCR confirmed that all TKp16L+/p53L+/+ tumors exhibited a recombination of K-Ras, p16INK4a and p53 alleles (Figure 1b). Western analysis of TKp16L+/p53L+/+ tumors demonstrated an absence of expression of p16INK4a and p53, as well as of p21cip1, a p53 target gene (Supplementary Figure 4a). These data demonstrate potent cooperation between activated K-Ras and combined p16INK4a and p53 loss in driving a highly penetrant and aggressive melanoma condition.

To further dissect the contributions of each tumor suppressor in melanoma development, we generated and compared TKp16L+ and TKp53L+ cohorts. These

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**Table 1** Summary of tumor features by genotype

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<th>Tumors/treated mice (%)</th>
<th>Median tumor latency</th>
<th>Metastasis</th>
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<tr>
<td>TK</td>
<td>1/14 (7)</td>
<td>&gt;52 weeks</td>
<td>None detected</td>
</tr>
<tr>
<td>Tk16L+/p53L+/+</td>
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</tr>
<tr>
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<td>3/7 (43)</td>
<td>&gt;52 weeks</td>
<td>None detected</td>
</tr>
<tr>
<td>Tk16L+/p53L+/+</td>
<td>15/15 (100)</td>
<td>9 weeks</td>
<td>None detected</td>
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*One lung tumor was noted in a 72-week-old animal of unclear histogenesis.*
animals were treated neonatally by topical 4-OHT and followed up for tumor development, as outlined in Supplementary Figure 1. Somatic, melanocyte-specific loss of either p16INK4a or p53 alone in this system led to melanoma formation (Figure 1a) with significantly longer tumor latencies than seen in the TKp16+/-p53+/- cohort but, notably, shorter than the latencies of the TKp16+/-p53+/- mice. Unexpectedly, the 4-OHT-treated TKp16+/- and TKp53+/- animals showed comparable median latencies of 24 and 31 weeks, respectively. The 4-OHT-treated compound heterozygous mice TKp16+/- and TKp53+/- showed accelerated tumorigenesis compared with 4-OHT-treated TK mice (Supplementary Figure 4b and Table 1). As expected, mice with somatic inactivation of p16INK4a and p53 without concomitant Ras activation (Tfp16+/-p53+/-) were only weakly tumor prone (1 of 19 mice, Table 1).

At the histopathological level, tumors from the four cohorts (TK, TKp16+/-, TKp53+/- and TKp16+/-p53+/-) exhibited a spindle-like morphology with scant pigmentation and positive staining for TRP1 (Figure 1c, Supplementary Figure 5). These ‘amelanotic’ melanomas are similar to those reported by Chin et al. (1997) in the H-Ras-driven Tyr Ras Ink4a/Arf−/− model, but different from the heavily pigmented tumors noted in N-Ras transgenic, Ink4a/Arf-deficient mice (Ackermann et al., 2005) and the conditional B-Raf and Pten mice (Dankort et al., 2009). In contrast to the Tyr Ras Ink4a/Arf−/− model, in which tumors are limited to ears, trunk, tail and uvea, tumors in the conditionally activable model occurred on the flank, ear and tail, and uveal tumors were not observed. An increased tumor multiplicity was noted in 4-OHT-treated TKp16+/- p53+/- mice compared with treated TK, TKp16+/- or TKp53+/- animals; however, there were significantly more tumors from treated TKp16+/-p53+/- mice when compared with TK, TKp16+/- or TKp53+/- animals, suggesting the increase in multiplicity could be due to an increase in the overall number of tumors (Supplementary Figure 4c). These data suggest that p16INK4a and p53 exert important and nonredundant antimitoma roles in the context of melanocyte-specific Ras activation, a finding that may reflect the prominent involvement of the Ink4a/Arf locus that dually encodes components of the RB and p53 pathway (Sherr, 2001).

Mice from all cohorts (TK, TKp16+/-, TKp53+/- and TKp16+/-p53+/-) developed melanocytic proliferation in the skin before tumor formation. Paws and tails of treated mice from all cohorts developed pigmented macules that were not present in wild-type or 4-OHT-untreated littermates (Supplementary Figure 6a and b). Wild-type and 4-OHT-untreated animals had little melanin production in sections of the ear when compared with treated mice from other cohorts. The most pronounced effects were observed in skin from 4-OHT-treated TKp16+/-p53+/- mice (Supplementary Figure 6c). These findings suggest that K-Ras activation alone is sufficient to produce a modest increase in melanocytic proliferation, and that this excess, nonmalignant proliferation is partially restrained by the combined activities of p16INK4a and p53.

To determine the role of the INK4–cyclin-dependent kinase 4 (Cdk4)–Rb pathway in melanocyte transformation in vivo, lysates of primary tumors were analyzed. In tumors from 4-OHT-treated mice of informative genotypes (TKp53+/-, TKp16+/-p53+/- and TKp16+/-p53+/-), the majority (8 of 11) of tumors demonstrated absent p16INK4a expression (Figure 2a and b). Recently, expression of p15INK4b has been shown to have a ‘back-up’ tumor suppressor role in p16INK4a germline-deficient animals (Krimpenfort et al., 2007; Ramsey et al., 2007). In tumors from animals with somatic p16INK4a and/or p53 inactivation, however, expression of p15INK4b was observed in 8 of 12 tumors (Figure 2c). Therefore, any such compensatory increase in p15INK4b expression either does not occur or is insufficient to prevent tumorigenesis in melanocytes in the setting of somatic deletion of p16INK4a. In aggregate, these results imply that acquired stochastic loss of p16INK4a, but not of p15INK4b, is commonly associated with in vivo tumor progression in melanocytes harboring somatic, but not germline, p53 inactivation.

Figure 2 Analysis of INK4–Cdk4/Cyclin–Rb pathway in representative melanomas. (a) and (b) Western analysis of p16INK4a and Arf in tumors of the indicated genotypes. (c) Western analysis of p15INK4b expression in tumors of the indicated genotypes. (d) Western analysis of phospho-p53 and Arf in tumors of the indicated genotypes.
Similarly, we analyzed the Arf–p53 pathway in lysates from tumors from mice of informative genotypes. In accordance with previous reports (Chin et al., 1997; Bardeesy et al., 2001; Sharpless et al., 2002), we noted that tumors lacking p53 function almost always exhibited a markedly increased Arf expression (Figure 2b and d). As expected, tumors from contemporaneously analyzed TyrRas Ink4a/Arf−/− mice showed Arf loss and expression of phosphorylated p53 (Figure 2d). Analysis of TKp16+/- tumors demonstrated that four of five tumors exhibited phospho-p53 expression (Figure 2d), whereas three of five tumors exhibited Arf expression (Figure 2a and d). In particular, at least two TKp16+/- tumors (#10 and 11, Figure 2d) exhibited phospho-p53 and retained Arf expression, consistent with the possibility of a retained Arf–p53 pathway function in these tumors. In tumors from 4-OHT-treated mice that were heterozygous for the floxed p53 allele, absent Arf expression was noted in two of five tumors (Figure 2b), suggesting that Arf loss can be associated with tumor progression even in a p53L+/+ background. Although some TKp16+/- tumors retained Arf–p53 expression, other TKp16+/- tumors lost Arf expression, suggesting that Arf loss can contribute to progression in some tumors. Overall, these results suggest that somatic inactivation of the Arf–p53 pathway can occur, but is not obligate, for progression of K-Ras-induced, p16INK4a-deficient melanoma.

In an effort to benchmark these new somatic models of melanoma to an earlier, well-characterized melanoma model, we also compared tumors from 4-OHT-treated TKp16+/-p53+/- mice with contemporaneously analyzed TyrRas Ink4a/Arf−/− mice (Chin et al., 1997). It should be acknowledged that several relevant biological differences limit this comparison, including somatic vs germ-line genetic events; single copy, endogenous K-Ras mutation vs multicopy, transgenic H-Ras mutation; and p53 vs Arf loss. Although the tumor-inducing genetic events occur later (postnatally) in the TKp16+/-p53+/- model, the tumor latencies were similar between the somatic and germine models (Figure 3a). Moreover, when the growth rates of comparably sized tumors were analyzed in vivo, melanomas from TKp16+/-p53+/- mice were noted to grow more rapidly with increased ulceration (Figure 3b). All tumor-bearing TKp16+/-p53+/- mice had to be killed by day 8 of observation because of advanced tumors, whereas TyrRas Ink4a/Arf−/− mice can routinely be observed for more than 20 days before having to be killed. Cell lines derived from TKp16+/-p53+/- tumors demonstrated increased S-phase and aneuploidy compared with TyrRas Ink4a/Arf−/− tumors (Figure 3c, Supplementary Table 1). Consistent

**Figure 3** TKp16+/-p53+/- melanomas are more aggressive than those from TyrRas Ink4a/Arf−/− mice. (a) Kaplan–Meier analysis of melanoma-free survival of TKp16+/-p53+/- (n = 15) and TyrRas Ink4a/Arf−/− (n = 12) mice (P = NS). (b) in vivo analysis of tumor growth of TKp16+/-p53+/- (n = 3) and TyrRas Ink4a/Arf−/− (n = 6) tumors. *P = 0.01 at days 6 and 8. (c) in vitro flow cytometry analysis of the cell cycle in tumor cell lines generated from TKp16+/-p53+/- and TyrRas Ink4a/Arf−/− tumors. Increased S-phase and aneuploidy are noted in tumors from TKp16+/-p53+/- mice (see also Supplementary Table 1). (d) Western analysis of indicated proteins in lysates from TKp16+/-p53+/- and TyrRas Ink4a/Arf−/− tumors.
with loss of p53 vs Arf inactivation, Arf levels were increased and p21CIP levels decreased in TKp16\(^{L/L}\)p53\(^{L/L}\) tumors compared with lines from TyrRas Ink4a/Arf\(^{-/-}\) tumors (Figure 3d). Further characterization of protein expression in tumor lysates from the different models indicated little difference in the expression of tested downstream mediators of Ras signaling (for example, phospho-ERK and phospho-AKT; Figure 3d). These results are consistent with the possibility of a more aggressive in vivo behavior of TKp16\(^{L/L}\)p53\(^{L/L}\) tumors as a result of p53 loss compared with Arf loss in the TyrRas Ink4a/Arf\(^{-/-}\) model, although other differences such as strain background or Ras isoform differences could also contribute. Importantly, however, despite technical and biological differences between the models, they share several common features including tumor histological appearance, lack of precursor nevus formation, scant or absent tumor pigmentation and lack of metastasis. The shared features of Ras-driven, p16\(^{INK4a}\)-deficient melanoma models are in contrast to the features of the pigmented, metastatic tumors seen in B-Raf mutant, Pten-deficient tumors reported by McMahon and Bosenberg (Dankort et al., 2009).

As epidemiological and murine modeling results have suggested that ultraviolet B exposure is more oncogenic at young ages, we studied the in vivo transformability of somatic K-Ras activation and combined p16\(^{INK4a}\)/p53 loss in adult mice. Toward this end, small (1 cm \(\times\) 1 cm) patches of flank skin were topically treated with 4-OHT in 8-week-old TKp16\(^{L/L}\)p53\(^{L/L}\) mice and then manually depilated to stimulate melanocyte proliferation (see Supplementary Figure 1 and Ruzankina et al., 2007). By 15 weeks post 4-OHT treatment, tumor development was observed in the majority (17 out of 27) of treated TKp16\(^{L/L}\)p53\(^{L/L}\) adult mice (Figure 4a and b), with all tumors developing at the site of 4-OHT treatment (Figure 4b and c). The median tumor latency of TKp16\(^{L/L}\)p53\(^{L/L}\) mice was modestly longer in animals treated as adults compared with neonates (Figure 4a), but this may be explained by the considerably more extensive CRE-mediated recombination observed in neonatally treated mice (not shown, see also (Bosenberg et al., 2006)). To serially monitor melanoma development in adult mice, a green fluorescent protein CRE-reporter allele was crossed into the TKp16\(^{L/L}\)p53\(^{L/L}\) model. Through intravital confocal microscopy of 4-OHT-treated TKp16\(^{L/L}\)p53\(^{L/L}\) adult mice, CRE recombination was confirmed in 4-OHT-treated skin, but not noted in untreated skin (Figure 4c). Despite a basal level of autofluorescence in untreated skin, all TKp16\(^{L/L}\)p53\(^{L/L}\)Rosa26-LSL-GFP\(^{+}\) tumors expressed green fluorescent protein, allowing for visualization of individual tumor cells in anesthetized, living mice. These data are not consistent with the model of a ‘developmental window’ for melanocyte transformability, but instead show that adult melanocytes can be efficiently transformed in vivo.

**Figure 4** Melanocytes from adult TKp16\(^{L/L}\)p53\(^{L/L}\) mice are transformable in vivo. (a) Kaplan–Meier analysis of melanoma survival of 4-OHT-treated TKp16\(^{L/L}\)p53\(^{L/L}\) mice as adults or neonatal pups. Control mice (4-OHT-untreated or lacking the K-Ras-LSL allele \((n = 9)\) did not develop tumors. Pairwise comparison of adult-treated \((n = 27)\) vs neonatally treated TKp16\(^{L/L}\)p53\(^{L/L}\) mice \((n = 15)\) \((P = 0.003)\). (b) Adult TKp16\(^{L/L}\)p53\(^{L/L}\) mice developed tumors in depilated and 4-OHT-treated skin patches. 4-OHT-treated control mice did not develop tumors. (c) Serial intravital confocal imaging of skin from TKp16\(^{L/L}\)p53\(^{L/L}\)Rosa26-LSL-GFP\(^{+}\) mice that were 4-OHT-treated as adults demonstrates green fluorescent protein expression and tumor growth. Melanocytes of untreated skin or of skin of control mice do not express green fluorescent protein; autofluorescence of hair follicles is noted. Original magnification: \(\times\) 200.
Discussion

In this study, we provide evidence that somatic $p16^{\text{INK4a}}$ deletion and oncogenic K-Ras activation promote the rapid onset of aggressive melanomas in vivo. To test somatic loss of $p16^{\text{INK4a}}$ in melanoma, a novel $p16^{\text{INK4a}}$ conditional allele was generated that exhibits unperturbed expression of either $\text{Ink}4\alpha/\text{Arf}$ locus genes, $p15^{\text{INK4b}}$ and Arf. We observed potent cooperation between somatic Ras activation along with somatic $p16^{\text{INK4a}}$ loss, whereas somatic Ras activation and p53 deletion yield a somewhat more modest melanoma-prone condition, a finding consistent the more prominent tumor suppressor role of $p16^{\text{INK4a}}$ relative to p53 in human melanoma. These data support the view that conditional inactivation of $p16^{\text{INK4a}}$ provides a more faithful platform for the generation of refined mouse models of human melanoma, and possibly of other cancers.

Moreover, as opposed to working using germline alleles (Kannan et al., 2003; Sharpless et al., 2003), the use of these conditional systems provides evidence that direct Arf-p53 inactivation is not required for in vivo murine melanoma formation. That is, some tumors arising in $TKp16^{L/L}$ mice (Figure 4d) exhibited Arf and phospho-p53 expression. Although the analysis of $TKp16^{L/L}$ tumors suggests that the ARF–p53 pathway retained expression, this does not eliminate other potential mechanisms that could abrogate the function of this pathway, such as point mutations or murine double minute 2 amplification. Nevertheless, although direct Arf or p53 inactivation does not seem to be an obligate event for in vivo melanomagenesis, our data and those of others certainly suggest that either lesion should strongly enhance tumor progression.

Although the primary tumors of $TKp16^{L/L}$ mice were aggressive in terms of local invasion, we did not detect metastasis, a hallmark of human melanoma. Although metastasis has been observed in both an N-Ras transgenic model that used a multicopy transgene with a presumed high level Ras activation (Ackermann et al., 2005) and a somatic B-Raf mutant and Pten mouse model of melanoma (Dankort et al., 2009), metastasis has otherwise not been a feature of most murine melanoma models involving Ras activation, p53 loss and $p16^{\text{INK4a}}$ loss (Chin et al., 1997; Burdeesy et al., 2001; Sharpless et al., 2003), suggesting that other factors are involved in metastasis in melanoma. One potential explanation could relate to Pten status, which is also inactivated with high frequency in human melanoma (reviewed in (Chin et al., 2006)). Several studies have suggested a prominent role for both the lipid and protein phosphatase activities of Pten in regulating cellular motility and invasion (Tamura et al., 1998; Marino et al., 2002; Raptopoulou et al., 2004; Lin et al., 2009). Similar to other large tumor suppressor genes that can be inactivated by a variety of mechanisms, studies of Pten in human cancer have been limited by difficulty in determining whether the gene is inactivated in a given tumor. Ongoing comprehensive studies such as the Cancer Genome Atlas involving multidimensional genome-scale analysis of large clinically annotated samples sets should determine whether PTEN loss is a primary driver of metastasis in human melanoma.

In summary, in this paper, we describe a genetically engineered murine model of melanoma that is based on somatic Ras activation and $p16^{\text{INK4a}}$ loss, which are hallmarks of the human disease. This study has shown that somatic inactivation solely of $p16^{\text{INK4a}}$, without the corresponding targeting of Arf, is potently tumorigenic in vivo. Inactivation of $p16^{\text{INK4a}}$ and p53 with Ras activation in adult melanocytes was potently oncogenic, suggesting that adult cells are not substantially less transformable than neonatal melanocytes. As novel targeted therapies for the RAS pathway are emerging for human melanoma (Engelman et al., 2008), these refined genetic models harboring genetic alterations encountered in the human disease should enable the more accurate use of such agents in specific melanoma genotypes in the future.

Materials and methods

Mouse colony

Animals were generated and genotyped as previously described (Johnson et al., 2001; Jonkers et al., 2001; Bosenberg et al., 2006) and were N1 in C57Bl/6. Mice were housed and treated in accordance with protocols approved by the institutional care and use committee for animal research at the University of North Carolina. Pups were treated for 3 consecutive days with 4-OHT (Sigma H7904, Sigma, St Louis, MO, USA) at 25 mg/ml in dimethyl sulfoxide starting at day 2 (Bosenberg et al., 2006). Tumor growth and survival were assessed three times per week by caliper measurements of tumor areas (width × length (mm²)) and measurement was taken when tumors were between 20 and 30 mm². Tumor growth was normalized to day 1 values and analyzed using GraphPad Prism software (GraphPad Software, La Jolla, San Diego CA, USA).

Generation of $p16^{L/L}$ allele and derivative cells

The $p16^{\text{INK4a}}$ conditional (floxed) allele ($p16^{L}$) was generated and validated as described in Supplementary Methods. To evaluate the effects of $p16^{\text{INK4a}}$ excision, 1 × 10⁶ murine embryonic fibroblasts were treated with CRE-expressing adenovirus (Iowa Vector Core, Iowa City, IA, USA) at a multiplicity of infection of 100 for 24 h. Cells were split and harvested 5 days after CRE treatment. To avoid the effects of adenoviral CRE expression on Arf-p53 expression, we crossed the $p16^{L}$ allele into lentiviral transgenic CRE-ER¹² mice (Ruzankina et al., 2007). Murine embryo fibroblasts containing the CRE-ER¹² transgene and homozygous for the $p16^{L}$ allele were generated and cultured on a 3T9 protocol. After four passages, cells were treated with 10 nm 4-OH-tamoxifen (Sigma T5648) for 40 h. After treatment, cell lysates were harvested at passages 1, 3 and 5. Primary melanocyte cultures from mice of the indicated genotypes, including the TyrCRE-ERT² allele, were prepared as described previously (Bennett et al., 1989; Spanakis et al., 1992) and plated on collagen-coated dishes. Cells were treated with or without 4-OHT at 20 days post isolation for 48 h. Successful recombination was confirmed at 22 days and western blot was performed at 45 days. For growth curve analysis, cells were counted at indicated times and replated at 3 × 10⁴ cells per ml. The mean relative population increase was calculated as the number of doublings.
Cell culture
Tumor cell lines were generated and maintained as described (Sharpless et al., 2002). For cell cycle analysis, exponentially growing cells were pulsed for 15 min with 10 μM bromodeoxyuridine (BrdU) in Dulbecco’s modified Eagle’s medium + 10% fetal calf serum before harvest. Cells were fixed, permabilized and stained with anti-BrdU-APC according to BrdU Flow Kit instructions (BD Pharmingen, San Jose, CA, USA) and then resuspended in phosphate-buffered saline + 0.2% fetal calf serum + 25 μg/ml propidium iodide with RNase and analyzed using a CyAn (Dako) flow cytometer (Cyan ADP, DAKO, Beckman Coulter, Brea, CA, USA) and FlowJo (Treestar, Inc., Ashland, OR, USA). Experiments were conducted in triplicate.

4-OHT treatment of adult mice and intravital microscopy
Hair on both flanks of 50- to 55-day-old mice was trimmed (1–2 cm² section) for treatment. One flank was treated with 20 mM 4-OHT dissolved in ethanol (treated skin) and the other with 0.2% fetal calf serum (control). Treatment was repeated the next day. Five days after treatment, mice were anesthetized with ketamine/xylazine and ear fur was removed using chemical depilation. Green fluorescent protein (GFP) expression was monitored by in vivo imaging 2-photon laser scanning microscope (Thornwood, NY, USA) using 900-nm light. Images were captured using a 12-bit cooled CCD camera (Hamamatsu, Bridgewater, NJ, USA).

Western blots
Western blot assays were performed on tumor lysates in RIPA buffer with protease inhibitors (Roche, Indianapolis, IN, USA) and phosphatase inhibitors (Calbiochem, EMD Chemicals Inc, Darmstadt, Germany) as described (Ramsey et al., 2007). Antibodies used were p21WAF (F-8, Santa Cruz, Santa Cruz, CA, USA), p16INK4a (M-156, Santa Cruz), p15INK4b (K18, Santa Cruz), p27KIP (M20, Santa Cruz), Cdk2 (M2, Santa Cruz), Cdk4 (C-22, Santa Cruz), β-actin (C-1, Santa Cruz), p-galactosidase (18G12, Promega) and phosphatase inhibitors (Calbiochem, EMD Chemicals Inc, Darmstadt, Germany) as described (Ramsey et al., 2007). Antibodies used were p21WAF (F-8, Santa Cruz, Santa Cruz, CA, USA), p16INK4a (M-156, Santa Cruz), β-actin (C-1, Santa Cruz), cyclin D1 (DCS-6, Cell Signaling, Danvers, MA, USA), cyclin E (M-20, Santa Cruz), Cdk2 (M2, Santa Cruz), Cdk4 (C-22, Santa Cruz), p15INK4b (K18, Santa Cruz), p27KIP (M20, Santa Cruz), phosho-p53 (Ser15, Cell Signaling), p53 (CM5, Novocastra Laboratories Ltd, Newcastle Upon Tyne, UK), p-ERK (9101S, Cell Signaling), ERK (9102, Cell Signaling), p-AKT (9271S, Cell Signaling), AKT (9272, Cell Signaling), Bax (Santa Cruz) and ARF (ab80, Abcam, Cambridge, MA, USA).

Immunohistochemistry
Assistance in sample processing was provided by the University of North Carolina Center for Gastrointestinal Biology and Disease. Ears and tumors were fixed in 10% formalin, paraffin-embedded, sectioned, deparaffinized and stained using hematoxylin and eosin for histological analysis. To confirm melanocytic origin, paraffin sections were treated with citric acid and stained with a rabbit anti-TRP-2 (gift from Vincent Hearing) at a dilution of 1:500, or without primary antibody for control samples. Detection was performed using highly sensitive DAKO EnVision polymerized horseradish peroxidase. β-galactosidase staining was previously described (Bosenberg et al., 2006). Samples were analyzed (Zeiss Axioskop 2) and photographed (Zeiss Axioscam) under bright-field microscopy using ×100.25 NA, ×200.50 NA and ×401.30 NA objectives.

Statistical analysis
Tumor-free survival was analyzed using GraphPad Prism software (GraphPad Software) and comparisons were made using the log-rank test. Tumor sizes were compared using an unpaired, two-tailed t-test. Error bars ± s.e.m.

Conflict of interest
The authors declare no conflict of interest.

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