Genetic Ablation of Cav1 Differentially Affects Melanoma Tumor Growth and Metastasis in Mice: Role of Cav1 in Shh Heterotypic Signaling and Transendothelial Migration

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Abstract

Both cell-autonomous and non-cell-autonomous factors contribute to tumor growth and metastasis of melanoma. The function of caveolin-1 (Cav1), a multifunctional scaffold protein known to modulate several biologic processes in both normal tissue and cancer, has been recently investigated in melanoma cancer cells, but its role in the melanoma microenvironment remains largely unexplored. Here, we show that orthotopic implantation of B16F10 melanoma cells in the skin of Cav1KO mice increases tumor growth, and co-injection of Cav1-deficient dermal fibroblasts with melanoma cells is sufficient to recapitulate the tumor phenotype observed in Cav1KO mice. Using indirect coculture experiments with fibroblasts and melanoma cells combined with cytokine analysis, we found that Cav1-deficient fibroblasts promoted the growth of melanoma cells via enhanced paracrine cytokine signaling. Specifically, Cav1-deficient fibroblasts displayed increased ShhN expression, which heterotypically enhanced the Shh signaling pathway in melanoma cells. In contrast to primary tumor growth, the ability of B16F10 melanoma cells to form lung metastases was significantly reduced in Cav1KO mice. This phenotype was associated mechanistically with the inability of melanoma cells to adhere to and to transmigrate through a monolayer of endothelial cells lacking Cav1. Together, our findings show that Cav1 may regulate different mechanisms during primary melanoma tumor growth and metastatic dissemination. Cancer Res; 1–13. ©2012 AACR.

Introduction

Tumors are heterogeneous microenvironments that consist of both neoplastic and nonneoplastic cells (tumor–stroma). Tumor growth and the consequent metastatic dissemination of tumor cells result from continuous reciprocal interactions between cancer cells and their surrounding stroma (1, 2). Cutaneous melanoma remains the most aggressive type of skin cancer and both cell-autonomous and non–cell-autonomous mechanisms are necessary for melanoma growth and metastasis (3). Recent research, in fact, has shown that stromal cells (fibroblasts and endothelial cells) support the growth and dissemination of melanoma cells by modulating angiogenesis, secreting growth factors and cytokines, and contributing to extracellular matrix deposition and degradation (4). Thus, identifying novel mechanisms critically regulating tumor–stroma interactions may be therapeutically relevant in this type of cancer.

Caveolae are specialized microdomains of the plasma membrane enriched in the scaffold protein caveolin-1 (Cav1; refs. 5, 6). Because of the multitude of interacting proteins described, Cav1 has been implicated in the modulation of many biologic processes in both normal tissues and cancer (7, 8). Although much research has primarily focused on determining the function of Cav1 in cancer cells, recent studies have started to investigate the function of Cav1 protein in the tumor microenvironment (9, 10). Indeed, Cav1 is highly expressed in endothelial cells and fibroblasts, two of the cell types that are normally involved in stromal remodeling during melanoma progression (3). In addition, the angiogenesis defects (11) and impaired skin wound healing (12) displayed by Cav1KO mice suggest that loss of Cav1 in the stromal compartment may functionally affect tumor–stroma interactions in melanogenesis.

To examine this issue, we used Cav1KO mice to determine whether stromal Cav1 may affect the growth and metastatic ability of B16F10 melanoma cells. We show that absence of Cav1 promotes the growth of intradermally implanted B16F10 melanoma cells in mice. Indirect coculture experiments and
co-injections of fibroblasts and melanoma cells show that lack of Cav1 in dermal fibroblasts promotes the growth of melanoma cells in vitro and in vivo via paracrine cytokine signaling. In contrast, the ability of B16F10 cells to form lung metastases in Cav1KO mice was significantly impaired. These results were consistent with the inability of B16F10 cells to transmigrate through a monolayer of human umbilical vein endothelial cells (HUVEC) lacking Cav1. Collectively, our data suggest functionally distinct roles for stromal Cav1 in melanoma primary tumor growth and metastasis.

Materials and Methods

Materials

Antibodies and their sources were as follows: Cav1 (N-20), PECAM-1 (M20), eGFP (sc-8334), and Shh (N-19) were from Santa Cruz. Keratin-14 (K14) was from Covance. Rat anti-mouse VCAM-1 and ICAM-1 were from R&D. Gli-1 was from Cell Signaling. β-Tubulin was from Sigma and glyceraldehyde-3-phosphate-dehydrogenase (GAPDH) was from Fitzgerald.

Animal studies

Three- to four-month-old Cav1WT (WT), Cav1KO (13), and Cav2KO (14) C57Bl/6 female mice were used for orthotopic and i.v. injections of B16F10 cells. For co-injection experiments, 3- to 4-month-old athymic female mice (NCr-Nu; Taconic) were used (15, 16). All in vivo studies were approved by the Institutional Animal Care and Use Committee of Thomas Jefferson University (Philadelphia, PA).

Cell lines

B16F10 and A-375 were from American Type Culture Collection, whereas human immortalized dermal foreskin fibroblasts (hTBJ1) were originally from Clontech. HUVECs were purchased from ALLCELLS. Only early passages of these cell lines were used in experiments.

Neonatal dermal fibroblasts

Dermal fibroblasts and primary mouse keratinocytes were isolated from the skin of newborn mice (1- to 3-day-old) as described in details by others (17). Fibroblasts were suspended in 10% FBS-Dulbecco’s Modified Eagle’s Media (DMEM; Invitrogen) and initially plated at a density of 5,000 cells per cm².

Co-injection experiments

Wild-type (WT), Cav1KO, and Cav2KO neonatal fibroblasts (see above) were intradermally co-injected with 10⁵ B16F10 cells in nude mice at 5:1 ratios. Similarly, hTBJ1 fibroblasts were co-injected with human A-375 melanoma cells (18, 19).

Lentiviral vectors

For lentivirus-mediated silencing of the Cav1 gene, predesignated control shRNAmiR (shCtrl-miR) and shRNAmiRs (shCav1-miRs) targeting the human CAV1 mRNA (NM_001753.3) were purchased from Invitrogen and subcloned into the pRRLsin.cPPT-IRES.eGFP.WPRE (LV-eGFP) lentiviral vector (20). The resulting constructs (LV-shCtrl-miR-eGFP and LV-shCav1-miRs-eGFP) were packaged according to standard protocols (20). Effective CAV1 knockdown in target cells was determined by Western blot analysis of fluorescence-activated cell-sorting (FACS)-sorted eGFP-positive cells. A lentiviral vector (LV105-Puro) encoding mCherry cDNA was from Gene-Copeoia whereas ready to use shCtrl-Puro and shGli-1-Puro (gene ID: 14632) lentiviral particles were from Santa Cruz.

Cocultures of fibroblasts and melanoma cells

Direct cocultures (direct cell–cell contact) were established by seeding 10⁴ cells per cm² mCherry-labeled melanoma cells on eGFP-labeled (shCtrl/shCAV1 cells) or on unlabeled fibroblasts (1:5 ratios) that had previously been serum-activated as described later for the conditioned medium (CM) experiments. Forty-eight or 72 hours after the initial plating (21), cocultures were harvested and their relative growth determined by flow cytometric analysis (FACS). Transwell cocultures of fibroblasts and melanoma cells (no cell–cell contact) were established as described earlier by using 0.4-μm pore size transwell membrane inserts (22).

Conditioned medium experiments

Conditioned medium was collected from dermal fibroblasts that were maintained in serum-free medium for 48 hours. Fibroblasts were then serum-activated (SA) by maintaining them for 12 hours in 10%FBS-DMEM and 24 hours in 1%FBS-DMEM (23). Conditioned medium from these cells (SA-CM) was then incubated with melanoma cells for 48 hours. For Shh-pathway inhibition studies, cyclosporine (Selleck) or dimethyl sulfoxide (DMSO) were added to conditioned medium for 48 hours. Recombinant Shh protein (PeproTech) was used for hedgehog signaling activation in melanoma cells.

Cytokine array and ELISA

Cytokine array and ELISA for ShhN were carried out on FB-CM using commercially available kits from RayBiotech and R&D.

Immunohistochemistry

S100 (RAb; Dako) immunohistochemical staining of 5-μm paraffin-embedded tumor sections was carried out as previously described by us (15).

Tumor angiogenesis

Microvessel density (MVD) was determined by CD31 (1:500; sc-1506) immunohistochemical staining of 5-μm paraffin-embedded tumor sections was carried out as previously described by us (15).

[³H]Thymidine incorporation assay and growth curves

DNA synthesis was determined by incubating asynchronously growing cells with 0.5 μCi/mL of [³H]thymidine (Perkin-Elmer) for 18 hours (27). Growth of melanoma cells was
assessed by MTT assay at 0, 24, 48, 72, and 96 hours after plating (28).

**Western blotting**

Homogenized tissue samples and cells were sonicated and lysed in a modified radioimmunoprecipitation assay buffer and processed for immunoblot analysis as previously described (26).

**Tumor–cell transendothelial migration assay**

HUVECs (5 × 10⁴) were grown to confluence (72 hours) on top of an 8-μm pore size gelatin-coated membrane (Transwells; BD Biosciences). A total of 1 × 10⁵ [³H]thymidine- or mCherry-labeled B16F10 cells in 500 μL of 0.1% bovine serum albumin (BSA)-DMEM were added to the Transwell inserts. Serum-free NIH3T3 conditioned medium (48 hours) was used as a chemoattractant. After 6 hours, Transwells were washed with PBS and wiped with cotton swabs. Membranes were removed and the amount of radioactivity determined by liquid scintillation counting (LSC; ref. 29). Alternatively, inserts were fixed with 4% paraformaldehyde, wiped with cotton swabs, and mounted onto glass slides. Migrated mCherry-B16F10 cells were imaged by confocal microscopy (LSM510.META.Confoocal; Zeiss).

**Tumor–endothelial cell adhesion assay**

[³H]Thymidine-labeled B16F10 cells (1 × 10⁵) were incubated on top of a monolayer of HUVECs in 0.1% BSA-DMEM at 3³C for 30 minutes. After being washed with PBS, cells were solubilized in 0.5N NaOH/0.1% SDS and the amount of radioactivity determined by LSC (29). For neutralizing antibody experiments, HUVEC monolayers were pretreated for 30 minutes with VCAM-1 (sc-20070), ICAM-1 (sc-59787), or IgG isotype control (10 μg/mL each; ref. 30).

**TNFα-induced ICAM-1 and VCAM-1 expression in mice**

Three- to four-month-old WT and Cav1KO female mice were intraperitoneally injected with 25 μg/kg of mouse recombinant TNFα (R&D). After 5 hours, mice were sacrificed and lungs were cleared of blood by infusing cold PBS through the right ventricle (31). The left lung lobe was then collected and processed for Western blot analysis (26).

**Statistical analysis**

Results are represented as means ± SEM. Statistical analysis was conducted using GraphPad Software.

**Results**

**Cav1 ablation in mice promotes the growth of B16F10 melanoma cells independently of Cav2**

To determine whether absence of Cav1 in the skin affects B16F10 cell growth, we examined the growth of B16F10 cells orthotopically (intradermally) implanted in the skin of WT and Cav1KO C57BL/6 female mice. After 18 days, analysis of tumor size revealed that their growth was enhanced (~2-fold) in Cav1KO mice (Fig. 1A). Caveolin-2 (Cav2) is normally coexpressed and hetero-oligomerizes with Cav1. Previous studies have reported reduced Cav2 levels in Cav1KO mice (13). Thus, the Cav1KO tumor phenotype may be confounded by Cav2 loss or reduced function. Relative to WT and Cav1KO animals, B16F10 cells implanted in the skin of Cav2KO mice grew more slowly (~1.5-fold), indicating that the Cav1KO tumor phenotype was Cav2-independent (Fig. 1B). Similar reductions in tumor growth were observed in subcutaneously injected Cav2KO mice (Supplementary Fig. S1), indicating a growth-promoting role for Cav2 in melanoma. CD31 immunohistochemical staining of Cav1KO tumor sections revealed increased MVD relative to WT and Cav2KO tumors, respectively. These results were corroborated by CD31 immunoblotts of whole-tumors lysates (Fig. 1C). Taken together, these findings suggest that growth of B16F10 in Cav1KO mice correlates with their MVD and this effect is independent of Cav2.

**Absence of Cav1 but not Cav2 in dermal fibroblasts enhances the growth of melanoma cells in co-injection experiments**

Dermal fibroblasts are the main cell components of the skin, which are important in maintaining the normal physiologic functions of this organ. To determine whether loss of Cav1 in dermal fibroblasts was sufficient to recapitulate the tumor phenotype observed in Cav1KO mice, dermal xenografts were established in nude mice by co-injecting WT and Cav1KO neonatal dermal fibroblasts with B16F10 melanoma cells at 5:1 ratios. After 14 days, analysis of tumor size showed that Cav1KO fibroblasts promoted the growth of B16F10 cells. S100b immunohistochemical staining (melanoma cell marker) and trichrome staining of tumor sections showed that collagen deposition and/or stromal cell proliferation was unchanged in B16F10/WT and B16F10/Cav1KO tumors (Fig. 2A). In contrast, the growth of tumors resulting from co-injecting B16F10/Cav2KO fibroblasts was comparable with the growth of their controls. Interestingly, immunoblot analysis revealed that Cav1 expression was maintained in Cav2KO fibroblasts, whereas Cav2 levels were slightly diminished in Cav1KO fibroblasts (Fig. 2B). The tumor-promoting role of Cav1-deficient fibroblasts was further shown by co-injecting human A-375 melanoma cells with hTBJ1-shCtrl or hTBJ1-shCAV1 fibroblasts in nude mice (Fig. 2C). Together, these results show that Cav1-deficient fibroblasts, but not Cav2KO cells, are sufficient to recapitulate the tumor phenotype of Cav1KO mice.

**Fibroblasts lacking Cav1 promote the growth of melanoma cells in noncontact cocultures but not in direct contact cocultures**

To investigate possible mechanisms whereby Cav1-deficient fibroblasts may promote B16F10 tumor growth, we cocultured (under cell–cell contact conditions) mCherry-B16F10 cells with serum-activated WT or Cav1KO dermal fibroblasts or mCherry-A-375 cells with serum-activated eGFP-labeled hTBJ1-shCtrl or hTBJ1-shCAV1 fibroblasts at 1:5 ratios in low-serum medium (1% FBS). After 48 and 72 hours, FACS analysis of mCherry-B16F10 or mCherry-A-375 cells revealed that Cav1-deficient fibroblasts were unable to promote the growth of melanoma cells under these conditions. Immunoblot analysis of primary Cav1KO fibroblasts or shCAV1 fibroblasts confirms...
absence/knockdown of Cav1 protein relative to WT and shCtrl fibroblasts, respectively. Furthermore, primary cultures were negative for the keratinocyte cell marker K14, confirming the purity of these cell populations (Fig. 3A and B). In contrast, a [3H]thymidine incorporation assay shows that proliferation of melanoma cells was significantly increased when cocultured (72 hours) with fibroblasts lacking Cav1 under noncontact conditions (Fig. 3C). These findings suggest that soluble secreted factors may be mediating the proproliferative effects of Cav1-deficient fibroblasts on melanoma cells.

**Serum-activated Cav1KO dermal fibroblasts display increased amounts of protumorigenic cytokines**

To determine whether Cav1 expression may regulate secreted soluble factors in fibroblasts, a cytokine array was done on conditioned medium from serum-activated WT and Cav1KO dermal fibroblasts. Conditioned medium from serum-activated Cav1KO fibroblasts displays increased amount of ShhN, basic fibroblast growth factor (bFGF), and matrix metalloproteinase (MMP)2/3, cytokines known to promote proliferation, invasion, and angiogenesis during melanomagenesis. Decoy receptors [hepatocyte growth factor receptor (HGFR), VEGF receptor (VEGFR2)] and an inhibitor of MMPs (TIMP1) were reduced in Cav1KO-CM (Fig. 4A). Increased expression of ShhN was also confirmed by ELISA assay and by immunoblot analysis of conditioned medium and cell lysates from Cav1-deficient fibroblasts (Fig. 4A). In addition, B16F10 cells incubated with conditioned medium from serum-activated Cav1KO fibroblasts (48 hours) display increased cell proliferation/growth and hyperactivation of the Shh signaling pathway as evidenced by increased cyclin D1/A and Gli-1 expression (an Shh target gene) and by increased [3H]thymidine incorporation and MTT assay (Fig. 4B). Similar outcomes were obtained when A-375 cells were incubated with conditioned medium from serum-activated hTBJ1-shCAV1 cells (Fig. 4A and C). Thus, our results indicate that fibroblasts lacking Cav1 secrete factors that promote proliferation, invasion, and angiogenesis.
Inhibition of Shh signaling pathway in melanoma cells reverses the proproliferative/protumorigenic effects of fibroblasts lacking Cav1

Recent studies have shown aberrant activation of Shh signaling in several cancer types including melanoma (32). To determine whether pharmacologic inhibition of the Shh pathway in B16F10 cells can reverse the proproliferative effect of Cav1KO-CM, we conducted a [3H]thymidine incorporation assay on melanoma cells incubated for 48 hours with Cav1KO-CM containing cyclopamine, a specific inhibitor of the Shh pathway. Our results show that low concentrations of cyclopamine (5–10 μmol/L) were effective in blocking the proproliferative effects of Cav1KO-CM on B16F10 melanoma cells. Interestingly, the proliferation of B16F10 cells incubated with WT-CM containing cyclopamine remains unchanged (Fig. 5A). Similarly, cyclopamine prevented the proproliferative effects of conditioned medium from serum-activated hTBJ1-shCAV1 cells on A-375 human melanoma cells (Fig. 5B). To examine whether inhibition of the Shh signaling pathway in B16F10 melanoma cells abolishes the protumorigenic...
Figure 3. Fibroblasts lacking Cav1 promote the growth of melanoma cells in noncontact cocultures but not in direct-contact cocultures. A, representative flow cytometric plots, photomicrographs, and quantification of B16F10-mCherry cells cocultured for 48 to 72 hours with SA-WT and SA-Cav1KO neonatal dermal fibroblasts in 1%FBS-DMEM (n = 5 per group). Cav1 and K14 (keratinocyte marker) immunoblots of freshly isolated dermal fibroblasts and keratinocytes are shown (right). B, representative flow cytometric plots, photomicrographs, and quantification of mCherry-A-375 cells growth, cocultured for 48 to 72 hours with SA-eGFP-labeled hTBJ1-shCtrl-miR or SA-hTBJ1-shCAV1-miR dermal fibroblasts in 1%FBS-DMEM (n = 5 per group). Cav1 and eGFP immunoblots of SA-hTBJ1-shCtrl-miR or SA-hTBJ1-shCAV1-miR are shown (right). β-Tubulin immunoblots are shown as loading controls. C, increased proliferation ([3H]thymidine incorporation assay) of B16F10 and A-375 cells cocultured in absence of cell–cell contact (Transwell; 48 hours) with SA-FBs lacking Cav1 (n = 5 per group). Results are means ± SEM (*, #, P < 0.05, by 2-tailed Student t test and by Dunnett’s multiple comparisons test; scale bar, 100 μm).

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Figure 4. SA-Cav1KO dermal fibroblasts display increased amounts of protumorigenic cytokines. A, left, cytokines differentially regulated in conditioned medium from SA-WT and SA-Cav1KO neonatal dermal fibroblasts; middle, ELISA showing increased ShhN levels in the conditioned medium of serum-activated dermal fibroblasts (SA-CM) lacking Cav1 ($n = 4$ per group). ShhN immunoblots of serum-activated dermal fibroblasts are displayed (right). B, MTT assay and $[^{3}H]$thymidine incorporation assay (48 hours) of B16F10 melanoma cells treated with SA-CM from WT and Cav1KO fibroblasts. Immunoblot analysis showing increased expression of Gli-1, cyclin D1, and cyclin A in B16F10 melanoma cells incubated (48 hours) with SA-CM from Cav1KO dermal fibroblasts ($n = 8$ per group). Similar results are shown (C) for human A-375 melanoma cells treated with SA-CM from hTBJ1-shCtrl and hTBJ1-shCAV1 cells. Results are means ± SEM ($n > 6$ per group; *, $P < 0.05$, by 2-tailed Student t test and by Dunnett’s multiple comparisons test).
Figure 5. Inhibition of Shh signaling pathway in melanoma cells reverses the proproliferative/protumorigenic effects of fibroblasts lacking Cav1. A, \[^3H\]Thymidine incorporation assay of B16F10 melanoma cells treated with DMSO or cyclopamine after incubation with SA-CM from WT and Cav1KO dermal fibroblasts. Representative phase-contrast images of B16F10 cells treated with SA-CM from WT and Cav1KO fibroblasts are shown on the right. Similar experiments (B) were done with A-375 cells incubated with SA-CM from hTBJ1-shCtrl and hTBJ1-shCAV1 cells. C, Gli-1 and β-tubulin immunoblots of B16F10-shCtrl, B16F10-shGli-1, and A-375 cells before and after being treated with Shh (left). Gli-1 knockdown in B16F10 cells reverses the tumor-promoting effects of Cav1KO fibroblasts as (right) determined by co-injection experiments. Results are means ± SEM (n = 4 per group; *, P < 0.05, by Tukey’s multiple comparisons test; scale bar, 200 µm).
properties of Cav1-deficient fibroblasts in vivo, we stably silenced the Gli-1 gene by lentiviral shRNA technology. Complete Gli-1 knockdown and reduced Gli-1 expression levels were achieved in absence and presence of Shh, respectively. Similar Gli-1 expression levels were also observed in A-375 cells treated with Shh, suggesting a fully functional Shh signaling pathway in both melanoma cell types (Fig. 5C, left). Co-injection experiments conducted as in Fig. 2A showed that Gli-1 knockdown in B16F10 cells was sufficient to reverse the tumor-promoting effects of Cav1-deficient fibroblasts (Fig. 5C, right).

In summary, these data show that Shh heterotypic signaling is critical for B16F10 melanoma cell proliferation and melanoma tumor growth when Cav1 is absent in dermal fibroblasts.

**Cav1 deficiency inhibits lung colonization and transendothelial migration of B16F10 melanoma cells**

Given the absence of spontaneous metastasis formation in B16F10 orthotopic tumor–bearing WT and Cav1KO mice (data not shown), we i.v. injected 10^5 B16F10 cells to determine their ability to colonize the lungs of WT and Cav1KO mice (experimental metastasis assay). Interestingly, the ability of B16F10 cells to colonize the lungs of Cav1KO mice was significantly impaired (Fig. 6A). To identify possible mechanisms accounting for these findings, we determined the ability of mCherry-labeled or [^3H]thymidine-labeled B16F10 cells to transmigrate through a monolayer of lentivirally transduced shCtrl and shCav1-HUVEC cells. Consistent with our in vivo data, the ability of B16F10 cells to adhere to and to transmigrate through a HUVEC monolayer was significantly reduced in CAV1 knockdown cells (Fig. 6B and C). Interestingly, incubation of HUVEC with ICAM-1 and VCAM-1 antibodies reduced the adhesion of B16F10 cells to levels similar to those observed with the HUVEC-shCav1, suggesting a critical role for Cav1 in regulating the process of metastatic extravasation (Fig. 6C, left). TNFα-induced VCAM-1 and ICAM-1 expression has been described as being critical in cancer cells–endothelium interactions (33). Interestingly, our in vitro results were corroborated by reduced VCAM-1 and ICAM-1 expression levels in lungs of 5h-TNFα-treated Cav1KO mice (Fig. 6C, right). Collectively, these results show that Cav1 has a key role in the endothelium and regulates processes such as adhesion and transmigration that are ultimately relevant for the establishment of lung metastases in vivo.

**Discussion**

In this study, we show that Cav1 gene disruption promotes the growth of B16F10 melanoma cells in the skin of mice, whereas it inhibits the formation of lung metastases. Our data indicate that lack of Cav1 in dermal fibroblasts contributes to primary melanoma tumor growth by increased paracrine cytokine signaling, whereas the inability of B16F10 cells to form lung metastases is attributed to defects in VCAM-1- and ICAM-1-mediated adhesion to endothelial cells.

Although the function of Cav1 has been recently examined in melanoma cancer cells (8, 15), the role of stromal Cav1 in melanoma tumor growth and metastasis remains less well studied. Here, we show that the difference in tumor growth seen in CavIKO and Cav2KO mice appears to correlate well with differences in their microvascular density. However, in contrast to our results, previous studies have shown reduced tumor growth and reduced MVD in CavIKO mice subcutaneously injected with B16F10 cells (34, 35), indicating that the injection site (intradermal vs. subcutaneous) and consequently the different tumor microenvironments may significantly affect melanoma tumor growth (36, 37). Although our findings are consistent with other studies showing a direct positive relationship between lack of Cav1 and higher microvascular density in vivo (11, 38), we cannot exclude the possibility that other stromal factors other than the endothelial cells are responsible for the Cav1KO and Cav2KO tumor phenotypes. Dermal fibroblasts, in fact, are abundant cellular components of the skin and they exert important biologic functions to maintain normal skin homeostasis (39).

On the basis of these findings, we postulated that Cav1-deficient fibroblasts promote the growth of melanoma cells by either direct cell–cell contact or paracrine signaling. To test this hypothesis, we did direct and indirect cocultures of fibroblasts and melanoma cells. Interestingly, our results from coculture experiments suggest that the growth-promoting features of Cav1-deficient fibroblasts may be attributed to enhanced paracrine signaling that does not require direct cell–cell contact. However, the inability of Cav1-deficient fibroblasts to promote the growth of melanoma cells in direct cell–cell contact cocultures may most likely be attributed to direct cell–cell contact inhibitory mechanisms exerted by normal fibroblasts (primary and/or immortalized cells) that are able to overcome the proliferative effects of secreted soluble factors. To identify possible secreted factors, we conducted a cytokine array on conditioned medium from serum-activated dermal fibroblasts. The increased secretion of cytokines, such as ShhN, MMP2/3, and bFGF, and the reduced expression of VEGFR2, HGF-R (decoy receptors; ref. 40) and TIMP1 (MMPs inhibitor) observed in Cav1KO dermal fibroblasts further confirms their protumorigenic phenotype, and this cytokine signature correlates well with the tumor phenotype of Cav1KO mice. In addition, these results are in agreement with many published studies that identified similar factors associated with the stromal remodeling of tumors (3, 41). A key finding of our study is the increased amount of the soluble form of the Shh protein (ShhN) observed in the conditioned medium of serum-activated Cav1KO dermal fibroblasts. Aside from having an essential role in embryonic development, Shh modulates many aspects of skin biology including wound healing (42), proliferation, and transformation (43). Furthermore, although Shh has been described to mainly function in an
autocrine manner in melanomagenesis (32), it is now becoming increasingly evident that Shh may contribute to tumor growth in a paracrine manner (44). Our results, showing increased DNA synthesis and increased Gli-1 expression in melanoma cells incubated with conditioned medium from Cav1-deficient fibroblasts, provide evidence that absence of Cav1 enhances Shh heterotypic signaling. Consequently, the proproliferative and protumorigenic

Figure 6. Cav1 deficiency inhibits lung colonization and transendothelial migration of B16F10 melanoma cells. A, left, experimental lung metastasis (mets) assay showing that the ability of B16F10 cells to colonize the lungs of Cav1KO mice is markedly reduced in (n = 9 per group). Representative images of WT and Cav1KO lungs dissected 18 days after i.v. injections of 10^6 B16F10 cells are shown (right). B, transmigration (6 hours) of mCherry- and/or [^3H]thymidine-labeled B16F10 cells across a confluent monolayer of HUVEC-WT, HUVEC-Lv-shCtrl, and HUVEC-Lv-shCAV1-#1/#2 (n = 4 per group). Representative images of transmigrated B16F10-mCherry cells are shown (right). C, adhesion assay of [^3H]thymidine-labeled B16F10 cells on confluent monolayers of HUVEC-shCtrl and HUVEC-shCAV1 untreated or treated with IgG1-isotype, ICAM-1, and VCAM-1 antibodies (n = 4 per group). VCAM-1, ICAM-1 immunoblots of lungs from TNFα-treated WT and Cav1KO mice (right). Results are means ± SEM (*, **, P < 0.05, by 2-tailed Mann–Whitney test and by Dunnett’s Multiple Comparisons test; scale bar, 100 μm).
effects of Cav1-deficient fibroblasts are reversed by inhibiting the Shh pathway with cyclopamine and by silencing Gli-1 in B16F10 cells.

Another important key finding of our study is the inability of B16F10 cells to form lung metastases in Cav1KO mice. The dissemination of cancer cells to metastatic sites is a stepwise process that begins with the invasion of the dermis surrounding the primary tumor and ends with metastatic extravasation and colonization of ectopic sites (36, 45). Metastatic extravasation from the bloodstream is a critical last step of the metastatic cascade that similarly to leukocyte transmigration requires the firm binding of cancer cells to the endothelial adhesion molecules VCAM-1 and ICAM-1. Blockade of VCAM-1- and ICAM-1-mediated interactions has been shown to effectively prevent the development of metastasis in a preclinical setting (30, 46, 47). Given these considerations, our adhesion assay results and our data showing reduced ICAM-1 and VCAM-1 expression in the lungs of TNFα-treated Cav1KO mice suggest that the inability of B16F10 cells to form metastases and to extravasate may be attributed to defects in VCAM-1- and ICAM-1-mediated adhesion to endothelial cells. Given our primary tumor results, the metastasis phenotype of Cav1KO mice appears quite paradoxical. However, recent work reveals that Cav1KO mice display several non-cancer-related phenotypes that support our observations. For instance, previous studies have shown that the resistance of Cav1KO mice to atherosclerosis development may be attributed to impaired endothelial VCAM-1 and ICAM-1 functions that ultimately result in reduced inflammation and impaired macrophage migration throughout the endothelium (48–50). Thus, it appears that similar endothelial defects may cause resistance to atherosclerosis and reduce melanoma metastasis in Cav1KO mice.

In summary, we show that loss of Cav1 promotes the growth of B16F10 tumors in the skin, whereas it suppresses B16F10 lung metastasis. Mechanistically, this phenotype is associated with enhanced paracrine cytokine signaling in Cav1KO dermal fibroblasts and with defects in endothelial cell–mediated transmigration of melanoma cells (Fig. 7). Thus, these findings support the notion that effective anticancer therapies will have to take into account the complex interactions between cancer cells and their microenvironment in both primary tumors and metastases.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

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