Pharmacologic Inhibition of MEK Signaling Prevents Growth of Canine Hemangiosarcoma

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Abstract

Angiosarcoma is a rare neoplasm of endothelial origin that has limited treatment options and poor five-year survival. As a model for human angiosarcoma, we studied primary cells and tumorgrafts derived from canine hemangiosarcoma (HSA), which is also an endothelial malignancy with similar presentation and histology. Primary cells isolated from HSA showed constitutive extracellular signal–regulated kinase (ERK) activation. The mitogen-activated protein/extracellular signal–regulated kinase (MEK) inhibitor CI-1040 reduced ERK activation and the viability of primary cells derived from visceral, cutaneous, and cardiac HSA in vitro. HSA-derived primary cells were also sensitive to sorafenib, an inhibitor of B-Raf and multireceptor tyrosine kinases. In vivo, CI-1040 or PD0325901 decreased the growth of cutaneous cell-derived xenografts and cardiac-derived tumorgrafts. Sorafenib decreased tumor size in both in vivo models, although cardiac tumorgrafts were more sensitive. In human angiosarcoma, we noted that 50% of tumors stained positively for phosphorylated ERK1/2 and that the expression of several MEK-responsive transcription factors was upregulated. Our data showed that MEK signaling is essential for the growth of HSA in vitro and in vivo and provided evidence that the same pathways are activated in human angiosarcoma. This indicates that MEK inhibitors may form part of an effective therapeutic strategy for the treatment of canine HSA or human angiosarcoma, and it highlights the use of spontaneous canine cancers as a model of human disease.

Introduction

Angiosarcoma is a malignancy of endothelial origin (1). Angiosarcoma is rare in humans, making up 1% to 2% of soft-tissue sarcomas (2) and having an estimated incidence of 0.2/100,000 persons per year. Current treatment options are limited to surgery followed by radio- and/or chemotherapy. Despite such treatment, the 5-year survival rate is 31% (3). Understanding of the biologic pathways driving this disease is crucial for developing novel therapies. To date, angiosarcoma has no clearly defined causative mutation, although activating mutations in key signaling molecules have been reported in angiosarcoma subtypes. For example, K-Ras2 mutations have been detected in 9 of 24 sporadic hepatic angiosarcomas (4) and also in hepatic angiosarcoma after occupational exposure to vinyl chloride (5, 6). Ten percent of angiosarcoma tumors showed activating mutations in KDR, the kinase insert domain receptor (also known as VEGFR2; ref. 7). Also, 25% of a 20-patient study of radiation-induced angiosarcoma showed a coamplification of Fms-related tyrosine kinase 4 (Flt4, VEGFR3) and MYC (8). Finally, mutations in PTEN (9) and phosphoinositide 3-kinase (PI3K; ref. 10) have been associated with angiosarcoma. The rarity of angiosarcoma has restricted the scope of basic and clinical research on this disease. Consequently, attention has turned to experimental models to generate further insight into its biology and treatment, including the study of more common (but related) human tumors, genetically engineered or chemically induced mouse models, and naturally occurring hemangiosarcoma (HSA) in companion dogs (reviewed in ref. 11). Dogs have a much higher incidence of HSA and a more rapid time course of disease progression than angiosarcoma in humans. The canine model also offers some unique, advantageous features that distinguish it from other animal models and that open novel experimental opportunities.
selective breeding, genetic variation within canine breeds is very low. Second, because each breed is derived from a small group of founders (most tracing back approximately 150 years), many of the genes associated with polygenic traits are fixed, so that only a few variable genes determine phenotype. This means it will be easier to identify genetic or biochemical determinants of disease in dogs than in humans. Finally, companion dogs share the same environmental exposures as humans and thus may more accurately reflect the human condition. The ability to identify, recruit, and study cancers within a breed of dog offers new avenues of hope for research in clinical oncology and into the underlying causes of angiosarcoma (12, 13). To gain insight into the biology of angiosarcoma, we began a study of naturally occurring canine model of angiosarcoma, which in dogs is commonly referred to as HSA.

By analogy to Kaposi sarcoma—another human endothelial malignancy resembling angiosarcoma, in which constitutive activation of viral G-protein-coupled receptor drives mitogen-activated protein/extracellular signal–regulated kinase (MEK) activity (14, 15)—we hypothesized that HSA growth and survival was dependent on MEK signaling. To test this concept, we treated tumor-derived canine primary cell isolates and xenograft tumors with agents targeting the Raf-MEK pathway. We found that MEK signaling played an important role in growth and survival of HSA. Our study indicated that MEK signaling was important in growth and survival of HSA. Our study indicated that MEK inhibitors may form part of an effective strategy for treatment of canine HSA or human angiosarcoma, and it highlighted the use of spontaneous canine cancers as a model for human disease.

Materials and Methods

Patient samples

Thirty deidentified, formalin-fixed, or optimal cutting temperature medium (OCT)-frozen angiosarcoma tumor samples were obtained from external sources, including the University of Michigan (Ann Arbor, MI), the Cooperative Human Tissue Network, and the Ontario Tumor Bank, which is funded by the Ontario Institute for Cancer Research (Toronto, ON, Canada). Angiosarcoma tumor pathology was independently reviewed by pathologists at the Van Andel Research Institute (VARI; Grand Rapids, MI).

Canine samples

Canine HSA tumor samples were collected from veterinary clinics following a protocol approved by the VARI Institutional Animal Care and Use Committee. Samples were shipped to VARI via overnight courier in ice-chilled PBS. Upon receipt of a sample, one portion was fixed in formalin, a second was snap-frozen in OCT medium, and the remainder was processed for cell culture as described later. Tumor pathology was reviewed independently by a pathologist specializing in canine oncology.

Cell culture

Tumors from canine HSA of the visceral, cutaneous, and cardiac subtypes were cut into 1-mm³ pieces with a scalpel. The tissue was transferred into an autoclaved flask containing 0.012 g of collagenase (Sigma-Aldrich) in 25 mL of Dulbecco’s modified Eagle medium (DMEM; Life Technologies) containing 10% heat-inactivated FBS (Life Technologies) and 1% penicillin/streptomycin (Life Technologies). The tissue was incubated overnight at 37°C with shaking at 85 rpm. Tissue was dissociated by trituration for 3 minutes using a 25-mL pipette and then centrifuged at 2,000 rpm in an Eppendorf 5810 centrifuge using a A-4-62 rotor (Eppendorf) at room temperature for 5 minutes. The pellet was resuspended in 20 mL of medium, triturated for 3 minutes, and then centrifuged as before; this was repeated twice. The cells were plated on a T75 tissue-culture flask and allowed to adhere overnight before washing to remove nonadherent debris. Cells were allowed to grow, and they then were collected and frozen at the initial and first passages (designated P0 and P1) for long-term storage in a liquid-nitrogen cryovessel.

For serum starvation, cells were grown to 80% confluence. They were then washed twice in PBS and incubated overnight (16 hours) in filter-sterilized serum starvation medium (DMEM containing 1% BSA and 1% penicillin/streptomycin).

Canine nerve sheath tumor endothelial cells (DNSTEC) were isolated by separating endothelial cells from tumor and stromal tissues using fluorescence-activated cell sorting (FACS). Canine endothelial cells were gated for CD31(+/−)/CD45(−)/αVβ3(+/−) cells using a FACS Aria High Speed Cell Sorter (BD).

Madin-Darby canine kidney (MDCK) cells (CCL-34) were obtained from the American Type Culture Collection. Upon receipt, these cells were expanded and frozen in multiple aliquots for subsequent use. Upon thawing, MDCK were grown in DMEM containing 10% heat-inactivated FBS and 1% penicillin/streptomycin. Cells were passaged every 2 to 3 days. As a rule, cells were passaged no more than nine times before a new aliquot was thawed for use. In some experiments, MDCK cells were washed with PBS and exposed to UV radiation using a UV Stratagene 1800 (Stratagene) for 1 minute to activate extracellular signal–regulated kinase (ERK). Growth medium was added back and cells were allowed to recover for 1 hour, after which they were lysed.

Cell viability assays

Primary cell isolates were grown in DMEM containing 10% heat-inactivated FBS, 1% penicillin/streptomycin, and 0.1 mg/mL of endothelial growth supplement (Thermo Fisher Scientific). Cell viability assays were conducted with cells between the first and fifth passages (P1 to P5). All assays were conducted in triplicate and each assay was independently replicated at least three times. Cells were seeded into 96-well tissue-culture plates in 100 μL of culture medium per well. Treatments began when cells reached 30% confluence. The medium was aspirated.
off, and 100 μL of fresh medium containing drug was added. Control wells received medium containing the appropriate vehicle. Cells were treated for 72 hours with CI-1040 (US Biologics), sorafenib-tosylate (LC Laboratory), or LY294002 (LC Laboratory; refs. 16–18). Cell viability was determined using the CellTiter 96 AQueous Non-Radioactive Cell Proliferation Assay (Promega) according to the manufacturer’s instructions. These assays were measured using a Benchmark Plus microplate spectrophotometer (Bio-Rad) at 490 and 700 nm reference wavelengths and were normalized against cells treated with medium plus vehicle only. The concentration of compound required to cause 50% inhibition of cell viability (IC₅₀) was calculated by linear regression.

**Immunoblotting**

Total cell lysates were collected in radioimmunoprecipitation assay (RIPA) buffer [50 mmol/L Tris–HCl, 150 mmol/L NaCl, 1 mmol/L EDTA, 1 mmol/L EGTA, 2 mmol/L Na₃VO₄, 20 mmol/L Na-pyrophosphate, 1% Triton X-100, 1% sodium deoxycholate, and 0.1% SDS, with Complete EDTA-free Protease Tablets (Roche Diagnostics) and phospho-S6 (S235/236; 2F9; Cell Signaling Technology), ERK (Cell Signaling Technology), and antibodies against phospho-ERK (Thr202/Tyr204; E10; Cell Signaling Technologies) and then transferred onto polyvinylidene difluoride (PVDF) membranes (Millipore). Membranes were blocked with 10% nonfat milk and then incubated with antibodies against phosphorylated ERK (phospho-ERK, pERK; Thr202/Tyr204; E10; Cell Signaling Technology) and CD31/PECAM-1 (2G11; Cell Signaling Technology) and CD31/PECAM-1 (2G11; Cell Signaling Technology) and then incubated with the appropriate secondary antibodies (anti-rabbit immunoglobulin G (IgG) secondary antibody (Ventana Medical Systems) and developed with 3,3’-diaminobenzidine (DAB) chromagen substrate. Formalin-fixed, paraffin-embedded (FFPE) tumors were sectioned. Immunostaining was conducted on the sections with optimized standard protocols using a Ventana Discovery XL instrument (Ventana Medical Systems) and antibodies against phospho-ERK (Thr202/Tyr204; 20G11; Cell Signaling Technology) and CD31/PECAM-1 (Lab Vision). Slides were incubated with HRP-conjugated anti-rabbit immunoglobulin G (IgG) secondary antibody (Ventana Medical Systems) and developed with 3,3’-diaminobenzidine (DAB) chromagen substrate.

**Microarray**

RNA was isolated from 18 angiosarcoma and normal human RNA was isolated from 3 kidney and 2 skeletal muscle OCT frozen sections and 3 samples of frozen...
whole blood. Twenty-five nanograms of total RNA from each sample was used for amplification, and then was fluorescently labeled using Cy3 and hybridized onto Agilent whole human genome 8 × 60k gene expression microarrays (Agilent Technologies) according to Agilent standard procedures. After hybridization for 17 hours at 65°C and 10 rpm, the arrays were washed and scanned with the Agilent G3 high-resolution scanner. Probe features were extracted from the microarray scan data using Feature Extraction software v.10.7.3.1 (Agilent Technologies). Microarray data were read and processed with R/Bioconductor (version 2.15.1/2.16) statistical software environment using the limma package (version 3.12.1). The raw data were within array quantile normalized and probes that mapped to the same gene were combined by averaging. Expression data for mitogen-activated protein kinase (MAPK) target genes reviewed in Yang and colleagues (22) were isolated. For each isolated gene, the average expression difference between angiosarcoma samples ($n = 18$) and the mean of control samples ($n = 10$) was determined. The genes with the highest magnitude of expression differences were isolated and plotted as a heatmap. The data discussed in this publication have been deposited in National Center for Biotechnology Information’s (NCBI) Gene Expression Omnibus (GEO) and are accessible through GEO Series accession number GSE44115.

Results

**MEK is active in HSA and HSA-derived primary tumor cells**

On the basis of its similarity to Kaposi sarcoma, we hypothesized that HSA was dependent on MEK signaling. To test whether MEK signaling is active in canine HSA, we ran immunohistochemical assays on FFPE tumor samples using antibodies against phospho-ERK1/2, which are direct substrates of MEK 1 and 2. HSA tumors were found to express phospho-ERK1/2, with the majority of the signal present in cells lining irregular blood vessels and areas near the outer portion of the tumor (Fig. 1A–O). Some internal focal expression was also seen. Phospho-ERK1/2 was detected in cutaneous, cardiac, and splenic HSA, and ranged from weak (Fig. 1L andO), to moderate (Fig. 1A, C and D–F), to very strong (Fig. 1B and M). In total, 9 of 15 tumors examined were positive. These results indicated that MEK signaling is a common feature among HSA subtypes.

For subsequent testing, we used primary cells derived from tumor samples. To test whether MEK signaling is active in primary cells derived from HSA, we conducted immunoblotting of HSA primary cells isolated from cutaneous, visceral, and cardiac tumors before and after serum starvation using antibodies against phospho-ERK and total ERK. DNSTECs were included for comparison, and MDCK cells treated with UV light were included as a positive control for ERK activation. HSA cells and DNSTECs growing in the presence of 10% serum had levels of phospho-ERK2 comparable to those observed in UV-treated MDCK cells (Fig. 2). In contrast, ERK1 phosphorylation was low or not detectable relative to UV-treated MDCK cells. Following serum starvation, ERK2 phosphorylation in DNSTECs was undetectable, but the levels of phospho-ERK2 in primary cells derived from HSA remained or increased. These data indicate that ERK2 is persistently active in HSA-derived primary cells.

**MEK signaling is required for in vitro proliferation of HSA-derived primary tumor cells**

To test whether MEK plays a role in the growth and proliferation of HSA, we treated primary cells derived from HSA with the MEK inhibitor CI-1040 and measured the inhibitor’s IC$_{50}$. HSA primary cell isolates from the three subtypes were treated for 72 hours in the presence of a range of CI-1040 concentrations. Assays showed that cell viability for all subtypes decreased in a dose-dependent manner, with IC$_{50}$ values of 2 to 8 μmol/L. In contrast, DNSTECs were relatively insensitive to CI-1040 and failed to reach 50% growth inhibition even at 10 μmol/L, the highest dose tested (Table 1). Inhibition of cell viability correlated with decreased ERK2 phosphorylation (Supplementary Fig. S1A and S1B). These results indicated that MEK signaling is important for in vitro growth and proliferation of HSA.

To test whether signaling pathways upstream of MEK play a role in the growth and proliferation of HSA, we treated primary cells with sorafenib, a drug targeting B-Raf and receptor tyrosine kinases such as VEGFR2. HSA primary cell isolates from the three subtypes were treated for 72 hours in the presence of a range of sorafenib concentrations. We observed that ERK phosphorylation (Supplementary Fig. S1C and S1D) and cell viability for all subtypes decreased in a dose-dependent manner, with IC$_{50}$ values from 2 to 6 μmol/L. DNSTECs were only modestly more sensitive to sorafenib, with an IC$_{50}$ of 8 μmol/L (Table 1). These results indicated that signaling pathways upstream of MEK are important for in vitro growth and proliferation of HSA cells, as well as for other proliferating endothelial cells.

Signaling through Ras activates Raf and PI3K/AKT signaling. To test for PI3K/AKT signaling, we treated primary cells derived from HSA with the PI3K inhibitor LY294002. HSA primary cell isolates from the three subtypes were treated for 72 hours in the presence of a range of LY294002 concentrations. Cell viability for all subtypes decreased in a dose-dependent manner, with IC$_{50}$ values of 9 to 30 μmol/L. Inhibition of cell growth correlated with decreased S6 phosphorylation (Supplementary Fig. S1E and S1F). In contrast, DNSTECs were relatively more sensitive to LY294002, with an IC$_{50}$ of 15 μmol/L (Table 1). These data indicated PI3K/AKT signaling is not critical for the in vitro growth and proliferation of primary cells derived from HSA. Collectively, these data showed that MEK/ERK specifically, and not any Ras downstream pathway, is important for HSA cell isolate viability.
HSA forms tumorgrafts in nude mice

Because in vitro cell growth does not accurately mimic all aspects of in vivo growth, we made several attempts to grow HSA-derived cells as xenografts or tumorgrafts in athymic nude mice. Unlike other sarcomas we have worked with (data not shown), HSAs do not readily grow in nude mice. Attempts to grow visceral tumors via intraperitoneal or intrasplenic injection and via tumor implants have so far failed (n=24). In contrast, when primary cells derived from cutaneous HSA were injected into the dorsal flank of athymic nude mice one of three primary cell cultures developed into tumors. Similarly, grafting of 2 mm³ portions of whole tumor derived from one of two cardiac HSAs into the dorsal flank of athymic nude mice also developed tumors. Once established, both the xenograft and the tumorgraft could be removed and subdivided for reimplantation or frozen for later reimplantation. These two HSA models were used to test the effects of different inhibitors on tumor growth in vivo.

The morphology of HSA cutaneous-derived xenograft and cardiac-derived tumorgrafts mimics that of the parental tumors

To confirm that xenografts and tumorgrafts retain key properties of HSA, FFPE sections were stained with hematoxylin and eosin (H&E) or probed with antibodies against CD31 and compared with parental tumors (Fig. 3). Cutaneous-derived xenografts generated lesions beginning in the upper dermis and extending deeply into subcutaneous tissue. The xenografts were composed of poorly circumscribed, expansile collections of intersecting fascicles of spindle-shaped tumor cells accompanied by...
rich admixture of vascular channels, as well as lumina lined by tumor cells having hyperchromatic and pleomorphic nuclei. Occasional interstitial clusters of neutrophils and mononuclear cells were present. CD31 expression in cutaneous HSA was strong, with diffuse positive staining on the spindle-shaped cells and the vascular lining cells. Overall, there was a remarkably strong similarity in light-microscopic patterns among cutaneous lesions pre- and postengraftment at both the histologic and immunohistochemical levels.

Cardiac tumorgrafts were characterized by admixtures of highly vascularized neoplastic cells with hyperchromatic and pleomorphic nuclei presenting as both lumen-lining channels and dispersed clusters of tumor cells. In addition, there were large areas of fibrinoid necrosis, nuclear debris, neutrophils, and scattered mononuclear cells. CD31 expression was strong and diffusely positive on those tumor cells both lining vessels and those in surrounding tissue. Cardiac-derived HSA lesions pre- and postengraftment also showed a high degree of similarity at the histologic and immunohistochemical levels. These observations indicate that the morphology of canine tumorgrafts is very similar to that of their parental tumors.

Sorafenib and CI-1040 inhibit MAPK activation and xenograft growth

To test whether MEK plays a role in growth of HSA in vivo, we treated HSA tumorgrafts with the MEK inhibitor CI-1040 for 42 days. In the first experiment, HSA cutaneous-derived xenograft fragments less than 50 mm³ in volume were implanted and treatment began the next day. Mice were dosed at 48 mg/kg, but on day 28, the dose of CI-1040 was decreased by 20% to avoid toxicity. Despite this, 3 treatment mice had to be sacrificed because of significant (>10%) weight loss. Tumor volume was measured three times weekly (Mon., Wed., and Fri.; Fig. 4A). At the completion of the experiment, the tumor burden of mice treated with CI-1040 was significantly smaller than that of untreated mice or of mice treated with vehicle alone (Fig. 4B). Decreased tumor volume correlated with ERK inhibition as shown by immunohistochemistry (IHC; Supplementary Fig. S2A–S2C). In the second experiment, HSA cardiac tissue-derived tumorgrafts were treated with CI-1040 at 38.3 mg/kg for 42 days beginning 1 day after implantation. Tumor volume was measured as described earlier. One mouse had significant weight loss (>10%) and was euthanized after 17 days of treatment.

### Table 1. Calculated IC₅₀ of HSA primary cell isolates and DNSTEC to small-molecule inhibitors

<table>
<thead>
<tr>
<th>Subtypes</th>
<th>Cell isolate</th>
<th>CI-1040 (µmol/L)</th>
<th>Sorafenib (µmol/L)</th>
<th>LY294002 (µmol/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>IC₅₀</td>
<td>IC₅₀</td>
<td>IC₅₀</td>
</tr>
<tr>
<td>Visceral</td>
<td>VCT12</td>
<td>2.7 ± 1.5</td>
<td>1.7 ± 1.3</td>
<td>24.1 ± 1.7</td>
</tr>
<tr>
<td></td>
<td>VCT61</td>
<td>3.0 ± 0.3</td>
<td>3.9 ± 2.9</td>
<td>29.7 ± 5.2</td>
</tr>
<tr>
<td></td>
<td>VCT75</td>
<td>2.4 ± 0.1</td>
<td>1.5 ± 0.6</td>
<td>16.2 ± 4.5</td>
</tr>
<tr>
<td>Cutaneous</td>
<td>VCT39</td>
<td>3.3 ± 1.1</td>
<td>2.8 ± 1.4</td>
<td>13.1 ± 2.3</td>
</tr>
<tr>
<td></td>
<td>VCT62</td>
<td>3.6 ± 2.6</td>
<td>5.8 ± 2.7</td>
<td>8.8 ± 3.4</td>
</tr>
<tr>
<td></td>
<td>VCT115</td>
<td>1.7 ± 0.7</td>
<td>2.4 ± 0.5</td>
<td>9.4 ± 2.9</td>
</tr>
<tr>
<td>Cardiac</td>
<td>VCT44</td>
<td>7.6 ± 5.6</td>
<td>4.0 ± 0.2</td>
<td>22.6 ± 4.2</td>
</tr>
<tr>
<td></td>
<td>VCT142</td>
<td>6.5 ± 4.4</td>
<td>2.3 ± 0.3</td>
<td>9.2 ± 4.0</td>
</tr>
<tr>
<td>DNSTEC</td>
<td>&gt;10 µmol/L</td>
<td>7.9 ± 3.2</td>
<td>14.7 ± 7.9</td>
<td></td>
</tr>
</tbody>
</table>
Like cutaneous HSA, cardiac-derived tumorgrafts showed variable rates of growth (Fig. 4C). Interestingly, while 5 of 6 treated mice showed a statistically significant reduction in tumor burden compared with nontreated or vehicle-treated mice, one tumorgraft displayed apparent resistance to CI-1040 treatment (Fig. 4D). If this resistant tumorgraft is included in the statistical analysis, the tumor volumes of the CI-1040-treated mice are no longer significantly different than tumor volumes of the nontreated group but remain statistically smaller than tumors from vehicle-treated mice. Decreased tumor volume correlated with ERK inhibition as shown by IHC (Supplementary Fig. S2D–S2F). To confirm efficacy of MEK inhibition on established tumors, cardiac-derived tumorgrafts were treated with the more potent MEK inhibitor PD0325901. Treatments were initiated when tumors reached a volume between 50 and 120 mm³. As in CI-1040-treated tumors, PD0325901 significantly decreased tumor growth compared with untreated and vehicle-treated tumors (Fig. 4E and F). These observations indicated cutaneous and cardiac-derived HSA tumorgrafts are sensitive to MEK1/2 inhibition.

To test whether signaling pathways upstream of MEK play a role in the growth and proliferation of HSA, we treated HSA cutaneous xenografts with sorafenib daily at 100 mg/kg for 42 days. Treatments were initiated approximately 2 to 5 weeks after implantation, when tumors reached a volume between 50 and 120 mm³. Six of 10 mice treated with sorafenib were euthanized before the completion of the experiment due to adverse toxicities including rash, hypothermia, and ascites. At the completion of the experiment, the tumor burden of 4 remaining mice treated with sorafenib was significantly smaller than that of untreated mice or of mice treated with vehicle alone (Fig. 5A and B). Decreased tumor volume correlated with ERK inhibition as shown by IHC (Supplementary Fig. S3A–S3C).

In the second experiment, cardiac-derived HSA tumorgrafts were treated with sorafenib starting when tumors reached a volume between 50 and 120 mm³. Growth rates were variable. Tumorgrafts implanted in nontreated and vehicle-control mice grew rapidly; several tumors reached a maximum allowed size of 1,000 mm³ within 3 weeks (Fig. 5C). These mice were sacrificed and their tumors saved, whereas the remaining mice continued on therapy. The final volume of these fast-growing tumors was compared with other tumor volumes at the completion of the
Figure 4. MEK inhibition reduces tumor growth in both cutaneous xenograft and cardiac-derived tumorgraft. A, growth curves of individual cutaneous xenografts. Arrowhead represents 20% decrease in drug concentration on treatment day 28. Arrow signifies a tumor estimated to be 10 mm$^3$. B, box-and-whisker plot of tumor volume at treatment day 42; the dot represents the fast-growing vehicle outlier. C, growth curves of individual cardiac-derived tumorgrafts. D, box-and-whisker plot of tumor volume at treatment day 42; the dot represents a CI-1040 refractory tumor. E, growth curves of average cardiac-derived tumorgrafts treated with PD0325901, vehicle, or nontreated ($n = 10$). F, box-and-whisker plot of tumor volume at treatment day 22. Error bars on growth curves represent SDs.
experiment. Thus tumor volume for nontreated and vehicle control mice shown in Fig. 5D is likely lower than it would have been had these tumors been allowed to continue grow for the duration of the experiment along with treated tumors. Despite this, it was apparent that sorafenib significantly inhibited the growth of cardiac-derived HSA tumorgrafts (Fig. 5D). Analyzed another way, sorafenib caused a significant reduction in the time taken for tumorgrafts to exceed three times their initial volume on treatment day 1 (Fig. 5E); in fact, four sorafenib-treated tumorgrafts never reached three times the initial volume. In addition, two tumors were resistant to
sorafenib. Decreased tumor volume correlated with ERK inhibition as shown by IHC (Supplementary Fig. S3D–S3F). These observations indicated cardiac-derived HSA tumorgrafts are sensitive to sorafenib-mediated inhibition of signaling pathways upstream of MEK.

**Canine HSAs are morphologically and histologically similar to human angiosarcoma**

To evaluate the extent of similarity between canine HSA and human angiosarcoma, we undertook a morphologic and immunohistologic comparison of the canine visceral, cutaneous, and cardiac HSA subtypes to their human counterparts.

**Canine visceral HSA.** Visceral HSA were highly vascularized infiltrative neoplasms characterized by scattered clusters of cuboidal-shaped cells having enlarged hyperchromatic and pleiomorphic nuclei with vesicular chromatin and nucleoli (Fig. 6A). The clusters were accompanied by anastomosing cords of cuboidal- and spindle-shaped cells with occasional multinucleation embedded in a highly vascular meshwork including the prominent presence of erythrocytes, pigment-laden macrophages, and large vessels surrounded by plasma cells and lymphocytes. Tumor cells were identified infiltrating the outer walls of large arteries and displayed perineural invasion. In some areas, flattened cells with elongated hyperchromatic nuclei lined aberrant vascular channels. Additional clusters of more epithelioid-appearing tumor cells having enlarged nuclei, prominent nucleoli, and abundant eosinophilic cytoplasm (occasionally containing multiple vacuoles) were also present, as were scattered mitotic figures. Immunohistochemical staining for CD31 revealed strong and diffuse reactivity of endothelial cells lining normal vessels as well as surrounding tumor cells of all morphologic subtypes, highlighting the plasma membranes of both normal and neoplastic cells (Fig. 6D).

**Canine cutaneous hemangiosarcoma.** Cutaneous HSA lesions were noncircumscribed, expansile, and infiltrative tumors extending from the upper dermis to include invasion into the underlying skeletal muscle. They comprised highly cellular intersecting fascicles of spindle-shaped cells and vascular channels with elongate pleomorphic and hyperchromatic nuclei and nucleoli embedded in a collagenous stroma with sparse mononuclear cell infiltration (Fig. 6B). The vascular channels were lined by cells of atypical appearance, some of which protruded into the lumens filled with erythrocytes accompanied by scattered mitotic figures. There were focal areas of extravasated erythrocytes, hemosiderin-laden...
channels, as well as in intratumoral foci. In total, 9 of 12 ERK1/2 signal was observed in both the cytoplasm and in cutaneous, visceral, and cardiac samples. Phospho-ERK1/2 (Fig. 7A and B). Phospho-ERK1/2 was not exclusive to any subtype of angiosarcoma; it was detected in archival FFPE specimens with antibodies against phospho-ERK1/2 (Fig. 7C). Myc and hypoxia-inducible factor-1α (HIF-1α) amplification has been previously noted in human angiosarcoma (8, 23). To further validate these results, we conducted IHC using antibodies against MEF2c. MEF2c showed strong nuclear staining and a weak to moderate diffuse cytoplasmic staining pattern in four of five human angiosarcoma examined (Fig. S4A). Similar staining was observed five of five canine HSA examined (Fig. S4C). MEF2c signal in angiosarcoma and HSA samples were above normal kidney signal (Supplementary Fig. S4B and S4D). Results of these two approaches are consistent with the hypothesis that MEK is active in human angiosarcoma.

Discussion

Angiosarcoma is a malignancy of endothelial origin (1). Its rarity has turned attention to experimental models for generating further insights into the disease (11). Studies in engineered rodent models are consistent with a role for MEK signaling in angiosarcoma. Injection of Moloney mouse sarcoma virus (24, 25), Harvey Sarcoma virus (26, 27), or Kirsten Sarcoma virus (28) into mice or rats induces the formation of angiomatous lesions resembling angiosarcoma or Kaposi sarcoma; these viruses encode mutant oncogenic forms of cellular oncogenes encoding c-mos, H-ras, and K-ras, respectively. Each of these genes stimulates cellular proliferation and oncogenic transformation by activation of the MAPK signaling pathway. Mice engineered to express knockin mutations (D1226N or Y1228C) in the activation loop of Met develop a high incidence of angiosarcoma with moderately pleomorphic endothelial cells, cavernous blood vessels, and palisading epithelioid-like cells (29). Met is a tyrosine kinase receptor for the hepatocyte growth factor/scatter factor and is a potent activator of the MAPK signaling pathway, regulating among other things the epithelial-to-mesenchymal transition and metastatic behavior (30).

To gain insight into the underlying biology of spontaneous angiosarcoma, we began a study of naturally occurring HSA in companion dogs. Although sharing many features in common with human angiosarcoma, HSA has a higher incidence and a more rapid progression. There is substantial variability of HSA among breeds, with larger dogs such as Golden retrievers and German shepherds having a much higher incidence. A health survey of Golden retrievers and German shepherds found several MAPK-responsive transcription factors, including SMAD1, TRIM24, MYC, HIF1α, and MEF2C were upregulated in a panel of angiosarcoma samples relative to RNA isolated from normal human tissue of mesodermal origin (Fig. 7C). Myc and hypoxia-inducible factor-1α (HIF-1α) amplification has been previously noted in human angiosarcoma (8, 23).

Hemangiosarcoma Is Sensitive to MEK Inhibition

The preceding data indicate human angiosarcoma and canine HSA share a similar pathology. To determine whether this similarity extends to a molecular level, we used two different approaches to assess MEK activity in human angiosarcoma. In the first, we immunostained archival FFPE specimens with antibodies against phospho-ERK1/2 (Fig. 7A and B). Phospho-ERK1/2 was not exclusive to any subtype of angiosarcoma; it was detected in cutaneous, visceral, and cardiac samples. Phospho-ERK1/2 signal was observed in both the cytoplasm and nucleus of cells lining normal and irregular vascular channels, as well as in intratumoral foci. In total, 9 of 12 tumors tested were positive for phospho-ERK1/2. In the second approach, we used OCT-frozen human angiosarcoma to evaluate the expression of a previously identified panel of MAPK-driven transcription factors (22). We found several MAPK-responsive transcription factors, including SMAD1, TRIM24, MYC, HIF1α, and MEF2C were upregulated in a panel of angiosarcoma samples relative to RNA isolated from normal human tissue of mesodermal origin (Fig. 7C). Myc and hypoxia-inducible factor-1α (HIF-1α) amplification has been previously noted in human angiosarcoma (8, 23). To further validate these results, we conducted IHC using antibodies against MEF2c. MEF2c showed strong nuclear staining and a weak to moderate diffuse cytoplasmic staining pattern in four of five human angiosarcoma examined (Fig. S4A). Similar staining was observed five of five canine HSA examined (Fig. S4C). MEF2c signal in angiosarcoma and HSA samples were above normal kidney signal (Supplementary Fig. S4B and S4D). Results of these two approaches are consistent with the hypothesis that MEK is active in human angiosarcoma.
selected traits in the directed evolution of these breeds. Whatever the answer, the genetic uniformity within breeds offers a unique and unbiased opportunity to identify factors promoting angiosarcoma.

HSA may present in virtually any tissue of the body. Although most dogs present with splenic or liver lesions, some breeds show elevated incidence of cutaneous HSA (e.g., Whippets and Italian greyhounds) or cardiac HSA (e.g., Saluki). This is notable because it shows that genetic factors not only influence susceptibility to HSA, but they also determine its location. From a research perspective, this opens new avenues for discovery of the basic mechanisms of the origin and progression of cancer, which could be translated to help our understanding of the causes and treatment of angiosarcoma in human patients.

In this study, we tested the hypothesis that HSA growth is dependent on MEK signaling. Using IHC on FFPE HSA samples, we observed isolated cells or clusters of tumor cells expressing phospho-ERK1/2 in 60% of samples examined. Furthermore, immunoblotting of lysates made from cultured primary cell isolates derived from canine HSA showed ERK1/2 activity even after serum starvation. These observations indicated MEK is active in canine HSA, but the cause of this aberrant MEK signaling is not known. We have sequenced for reported mutations in several candidate genes including VEGFR and B-Raf, but to date we have not identified any activating mutations. The fact that MEK signaling was present only in isolated cells or clusters of tumor cells indicates that ERK1/2 is transiently phosphorylated or that ERK1/2 phosphorylation in subset of cells is sufficient for tumor growth. This is reminiscent of Kaposi sarcoma, another endothelial malignancy, in which proliferating spindle cells release cytokines that drive tumor growth in a paracrine fashion. Consistent with this, elevated levels of VEGF and bFGF, as well as Flt4 (VEGFR3) and FGFR-1, have been detected in association with canine angiosarcoma (32, 33) and human angiosarcoma (7, 8, 34).

Interestingly, HSA cellular isolates showed a predominance of ERK2 phosphorylation over ERK1. This is consistent with published data indicating that ERK2 may play a more prominent role in cancer. In a recent study using
breast cancer cells, von Thun and colleagues (35) reported that knockdown of ERK2 but not ERK1 decreased cell motility in a three-dimensional (3D) microenvironment. Similarly, Vantaggiato and colleagues (36) reported that knockdown of ERK2 but not ERK1 in NIH 3T3 cells reduces Ras-mediated colony formation. These reports indicate that ERK1 and ERK2 may have nonredundant roles in tumor growth and metastasis.

Canine tumor tissues represent a valuable resource for cell-based studies. In our experience of culturing more than 400 canine tumors, approximately 50% will grow in culture for two or more passages. Our success rate in culturing HSA is comparable: we successfully cultured 101 of 203 HSA for two or more passages. We are uncertain why some tumors grow well in culture, whereas others do not. In contrast to parental tumors, 60% of which had ERK1/2-positive cells, cultured HSA uniformly expressed active ERK1/2 even after 24 hours of serum starvation. This raises the possibility that in making tumor-derived cell cultures, we may have selected for a subset of tumors with active MEK signaling. Consistent with this, we observed that pharmacologic inhibition of MEK signaling reduced the viability of these cells in vitro. Thus, caution should be used not to extrapolate our in vitro data to represent all HSA. Indeed, an earlier study by Tamburini and colleagues (37) noted ERK activation in only 1 of 3 cell isolates tested, which is more in line with our observations in parental tumors. In addition, there is a concern that we may have selected for the growth of noncancerous cells in vitro. However, our observations that isolated cell cultures show persistent MEK signaling (Fig. 2) and aneuploidy (array CGH data not shown) indicate that tumor-derived cell cultures are a heterogeneous mixture of tumor and tumor-associated stromal cells that retain features in common with their tumor of origin.

Although we have been able to grow cardiac and cutaneous HSA-derived cells as tumorgrafts or xenografts in athymic nude mice, we have been less successful with visceral HSA-derived cells. This is a strong indication that either in vitro cell culture selects for cells with divergent growth abilities or the microenvironment in a mouse is substantially different from that of a dog. Additional growth supplements or modified growth conditions may be required to preserve their ability to grow in vivo. Despite this, those cells or tumors that did grow in vivo had morphology indistinguishable from their parental tumors. This provided us with an opportunity to test the necessity of MEK signaling for HSA growth in vivo.

We observed that although both cutaneous HSA xenografts and cardiac HSA tumorgrafts were sensitive to MEK1/2 inhibition by CI-1040, cardiac tumorgrafts were more sensitive to sorafenib (Figs. 4 and 6). Also, cardiac HSA tumorgrafts were sensitive to a second MEK inhibitor PD0329901 (Fig. 4E and F). These results show that MEK signaling is necessary for growth of HSA in vivo and provide a strong rationale for clinical evaluation of MEK inhibitors, either alone or in combination, for the treatment of HSA. Although, we cannot rule out sorafenib sensitivity is through inhibition of VEGFR2 or other in vivo targets. Our observations that ERK1/2 phosphorylation is detected in human angiosarcoma and that MEK/ERK-responsive transcription factors are upregulated in human angiosarcoma, suggest a similar approach for treating patients diagnosed with angiosarcoma. Indeed, in a recent report, Italiano and colleagues (10) noted ERK phosphorylation in 12 of 39 human angiosarcomas and concluded that inhibition of ERK signaling may be a relevant approach for their treatment. However, a larger cohort of angiosarcoma samples will be required to definitively translate the importance of MEK signaling from our canine model to angiosarcoma. Historically, studies with MEK inhibitors in other tumors have for the most part proven ineffective in clinical trials (reviewed in ref. 38). However, more recent clinical trials using the MEK inhibitor trametinib have shown promising results alone and in combination with a B-Raf inhibitor (reviewed in ref. 39). Thus, it may be prudent to consider using newer MEK inhibitors such as trametinib or a combination of an earlier MEK inhibitor plus a drug targeting other critical pathways for the treatment of HSA.

In summary, using naturally occurring HSA in companion dogs, we have shown that MEK signaling is essential for growth of HSA in vitro and in vivo. In addition, we have provided evidence indicating that the same pathways are activated in human angiosarcoma. Our study indicates that MEK inhibitors may form part of an effective therapeutic strategy for treatment of canine HSA or human angiosarcoma and highlights the use of spontaneous canine cancers as a model for human disease.

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

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