Endothelial ALK1 Is a Therapeutic Target to Block Metastatic Dissemination of Breast Cancer

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Abstract

Exploration of new strategies for the prevention of breast cancermetastasis is justifiably at the center of clinical attention. In this study, we combined a computational biology approach with mechanism-based preclinical trials to identify inhibitors of activin-like receptor kinase (ALK) 1 as effective agents for blocking angiogenesis and metastasis in breast cancer. Pharmacologic targeting of ALK1 provided long-term therapeutic benefit in mouse models of mammary carcinoma, accompanied by strikingly reduced metastatic colonization as a monotherapy or part of combinations with chemotherapy. Gene-expression analysis of breast cancer specimens from a population-based nested case-control study encompassing 768 subjects defined endothelial expression of ALK1 as an independent and highly specific prognostic factor for metastatic manifestation, a finding that was corroborated in an independent clinical cohort. Overall, our results suggest that pharmacologic inhibition of endothelial ALK1 constitutes a tractable strategy for interfering with metastatic dissemination of breast cancer.

Note: Supplementary data for this article are available at Cancer Research Online (http://cancerres.aacrjournals.org/).

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Introduction

Exploration of new strategies for the prevention of breast cancer metastasis is justifiably at the center of clinical attention (1). The haematogenous dissemination of tumor cells is a multistep process requiring: (i) detachment of malignant cells from the primary tumor, (ii) intravasation into and extravasation from the blood stream, and (iii) colonization of the distant organ (2). However, we currently have limited knowledge on the molecular drivers contributing to each of the steps in the metastatic cascade in breast cancer, and thus efforts to target-specific signaling pathways involved in the systemic spread of the disease have largely been unsuccessful so far (3). In cases where breast tumors are found in early stages, the prognosis following adequate therapy is good with a 3-year overall survival (OS) rate reaching above 90% (4). Nevertheless, many women are not diagnosed until the tumor has reached advanced stages; tumor stage is an established factor for poor prognosis (4). Thus, novel treatment strategies to combat disseminated breast cancer, both for the neoadjuvant and the adjuvant setting, are sorely needed.

The angiogenic process is required for tumor progression from an indolent state (5). The vascular tree provides a tumor with its metabolic requirements, while simultaneously providing an escape route by which malignant cells can leave the primary tumor bulk. Indeed, in particular cases, high vascular density was demonstrated to be a prognostic factor for poor outcome in breast cancer, as well as in other malignancies (6, 7). The introduction of multitargeted agents incorporating antiangiogenic activity in clinical practice has led to improved disease control in terms of prolonged progression-free survival (PFS). Consequently, drugs targeting the vascular endothelial growth factor (VEGF) pathway are now included in the first line therapy for metastatic disease for a range of malignancies (8–11). However, attempts to target tumor angiogenesis in breast cancer has met with ambiguous success (12, 13). Although providing initial relief for metastatic breast cancer patients by improving response rates and prolonging PFS, no conclusive evidence for long-term benefit in OS has been provided to date (13). Consistent with this clinical reality, recent preclinical studies indicate that tumors in mice treated systemically with anti-VEGF therapy rapidly acquire resistance, coupled to recurring tumors that appear to be more locally invasive and have a higher propensity to seed distant metastases (14–16). Thus, the need for a mechanism-based and clinically relevant search for alternative angiogenic pathways that may serve as targets for more efficacious drugs without affecting disease stage in breast cancer is highly warranted.

ALK1 is a type I receptor in the large TGFβ family expressed selectively by endothelial cells (17). Pharmacologic targeting of ALK1 has demonstrable therapeutic efficacy in a diverse set of mouse models of cancer (18–20). Here, we investigate the utility of ALK1 inhibition as an antimetastatic therapy in breast cancer using a combined approach of preclinical testing of a clinically
tractable ALK1 inhibitor and analysis of gene-expression patterns relating to metastatic spread in breast cancer patient specimens.

**Materials and Methods**

**Cell culture**

MDA-MB-231 were maintained in culture in DMEM (Invitrogen), supplemented with 10% FCS. EO771 breast cancer cells were cultured in DMEM supplemented with 20% FCS.

**Animal care and tumor establishment**

All animal experiments were approved by the local ethical committee for animal care in Stockholm and Lund (permits N96/11 and M142/13). The RIP-TAg2 mice (C57Bl6/J background) were injected orthotopically, received water supplemented with 5% sugar to alleviate hypoglycemia from 10 weeks of age. Total tumor burden per mouse was calculated as the sum of the volume of each individual tumor dissected from a RIP-TAg2 mouse pancreas. The MMTV-PyMT mice (FVB/n strain background) were followed for tumor growth from 8 to 12 weeks in early-stage trials and from 11 to 15 weeks of age in late stage trials. Primary tumor burden was determined by caliper measurements on live sedated mice once a week and the total tumor burden per mouse was calculated as the sum of the volume of each individual mammary tumor. To establish EO771 tumors, 5 x 10³ cells were injected orthotopically into the fourth mammary fat pad of isoflurane-anesthetized wildtype C57Bl6/J females. 1 x 10⁶ cells of the human metastatic breast cancer cell line MDA-MB-231 were transplanted s.c. to immunocompromised SCID mice. In all cases, tumor volume was calculated as length x width² x 0.6/π.

**Therapeutic trials**

Control IgG or RAP-041 (Acceleron Pharma) was diluted in TBS and administered twice weekly by i.p. injection at 12 mg/kg per injection. Mice carrying orthotopic EO771 mammary carcinomas were treated with either RAP-041 or IgG2a for 2 weeks starting 7 days following tumor establishment. Treatment with docetaxel (Taxotere, Sano-Parke-Davis) was incubated at 4°C overnight, followed by embedding in cryopreservation media. Frozen sections were fixed in ice-cold acetone, followed by blocking using serum free protein block (DAKO) for 20 min at 95°C. Blocking was performed in 10% PBS for 10 minutes in room temperature. A wash in PBS preceded blocking with 10% normal goat serum in TNB for 1 hour. The primary antibody against T-Ag (1:1,000; a kind gift from Douglas Hanahan, EPFL) was incubated at 4°C overnight. After washes with PBS containing 0.1% Tween-20, a suitable biotinylated secondary antibody was incubated for 45 minutes in room temperature.

For cryopreservation, tumors, livers and/or lungs were kept in 30% sucrose at 4°C overnight, followed by embedding in cryo-sectioning media. Frozen sections were fixed in ice-cold acetone, followed by blocking using serum free protein block (DAKO) for >30 minutes at room temperature. Primary antibodies directed against CD31 (dilution 1:100; Pharmingen M1C13.3), podocalyxin (dilution 1:100; R&D Systems, AF1556), and BMP9 (dilution 1:500; Abcam; ab35088) were incubated overnight at 4°C. Appropriate Alexa 594 and Alexa 488–fluorochrome-conjugated secondary antibodies (Invitrogen) were used and sections were finally mounted using 4’,6-diamidino-2-phenylindole-containing mounting media (Vector Laboratories).

**Quantification of metastases**

The right lateral liver lobe from RIP-TAg2 mice or the left lung lobes of MMTV-PyMT or EO771-bearing mice were embedded in paraffin upon tissue fixation. The metastatic burden was assessed by serial sectioning of the entire lung/liver lobe. Following hematoxylin and eosin (H&E) staining on every 25th section, the number of metastatic foci (>8 cells in diameter) was determined in >15 sections per mouse and >5 mice per group.

**RNA isolation and quantitative RT-PCR**

Total RNA of 12-weeks-old MMTV-PyMT mice mammary tissue was isolated using TRlzol extraction (Invitrogen), followed by the RNeasy Mini Kit (Qiagen) according to the manufacturer’s instructions. A 1 µg total RNA was subsequently used to generate cDNA using the iScript cDNA Synthesis Kit (Bio-Rad). Quantitative reverse transcription PCR was performed using the KAPA SYBR Fast qPCR Kit (Kapa Biosystems) on a Rotorgene 6000 (Qiagen) in triplicates using primers purchased from Qiagen: RPL19, TGFβ, BMP9/GDF2, BMP10, and GDF5 (QuantiTect primer Assays QT00166145, QT001455250, QT00307587, QT00259847, and QT00250523, respectively). Primers for analysis of Id1 and Id3 as in ref. 18.

**Tumor grade assessment**

To assess the tumor grade of lesions from MMTV-PyMT mice, tumor tissue was classified into different degrees of progression by quantifying the area of transformed glands occupied by each
stage. Progression follows from normal fat tissue to a “precan-
cerous stage” characterized by premalignant hyperplasia and
adenoma (with the retention of some normal ductal and acinar
mammary gland morphology), to a more epithelial cell—dense
“early carcinoma” with stromal invasion, and finally to an inva-
sive, very dense, high—mitotic index “late-stage carcinoma.”

Tumors were evaluated for the proportion of mammary fat
tissue, hyperplastic tissue, adenoma, early carcinoma, and late
carcinoma.

Clinical datasets
Expression data from The Cancer Genome Atlas (TCGA; http://
cancergenome.nih.gov/) were downloaded in November 2013.
The data were log2 transformed after addition of 1 to each
normalized value. Clinical and follow-up data were downloaded
in May 2014. All analyses were done with R using the basic and
survival packages. Breast cancer subtypes were determined using
nearest correlations with the PAM50 centroids.

The nested case—control study gained approval by the ethics
committee at Karolinska Institutet, Stockholm, Sweden. The
detail of the study design, collection of clinical-pathologic
information, gene-expression profiling of fresh frozen tumor
tissue and subsequent preprocessing and normalization of
microarray gene-expression data, and finally conditional logis-
tic regression modeling of the nested case—control study have
been reported elsewhere (array data deposited at the Gene
Expression Omnibus Database under accession number
GSE48091; ref. 21), and is the subject of a separate report
(Lindström and colleagues; submitted for publication). Gene-
expression data were collapsed to gene level using a nonspecific
filter keeping only the probe sets with highest interquartile
range in the case of multiple mappings to the same Entrez Gene
ID. As in the original publication, out of seven considered
clinical-pathologic variables—estrogen receptor (ER), progres-
teron receptor and HER2 status, histologic grade, prolifera-
tion, tumor size, and lymph node status—three variables,
namely lymph node status, tumor size, and HER2 status, were
considered significant and included in multivariable condition-
alogistic regression models. A missing category was used to
handle missing values in clinical-pathologic data. All gene-
expression data analysis and statistical analysis were done in
R/Bioconductor.

Statistical analysis
Unless specifically stated, all measurements are depicted as
mean ± SD. Statistical analyses for tumor volume were per-
formed using an unpaired, two-tailed Student t test. Statistical
analyses for tumor characteristics were performed using a
Mann–Whitney U test. Statistical significance was considered
using α = 0.05.

Results
Long-term inhibition of ALK1 impairs metastatic
dissemination and prolongs survival in an experimental model of
neuroendocrine tumorigenesis
We, and others, have previously documented the emergence of
therapeutic resistance toward anti-VEGF therapy using various
pharmacologic agents (14–16). Evasive resistance to VEGF-inhib-
itory modalities is accompanied by a hypoxia-driven maligniza-
tion, that is, enhanced local invasion and increased rate of
metastatic seeding, of tumors in the prototypical RIP-TAg2 mouse
model of angiogenesis-dependent pancreatic neuroendocrine
tumorigenesis (NET). To investigate whether antiangiogenic ther-
apy by inhibition of ALK1 signaling gives rise to a similar exacer-
bation of systemic dissemination, we contrasted previously per-
formed short-term therapeutic trials (18) with a long-term regi-
men of single-agent neoadjuvant therapy using ALK1-Fc, a ligand
trap that neutralizes BMP9 and BMP10 (RAP-041, mouse coun-
terpart of dalantercept; Fig. 1A). Regardless of the length or timing
of the treatment of RIP-TAg2 mice, single-agent RAP-041 gave rise
to a state of stable disease during the course of the trials, in contrast
with tumors in control-treated mice that consistently presented
with overt progressive disease (Fig. 1B and ref. 18). Despite
inducing a demonstrable reduction in vessel area, average vessel
length and the number of vessel endpoints, as judged by immu-
nostaining for the endothelial cell markers podocalyxin or CD31
(Fig. 1C and data not shown), RAP-041 did not provoke wide-
spread hypoxia, using CA IX or HIF1α expression as proxies for
low tissue oxygenation (Fig. 1D). Pancreatic NETs of RIP-TAg2
mice disseminate predominantly to sentinel lymph nodes in the
mesentery and to the liver, similar to the corresponding human
disease (Fig. 1E; ref. 22). The incidence of hepatic metastases in
RIP-TAg2 mice was not changed following short-term therapy
with RAP-041 (Fig. 1F). Strikingly, however, upon long-term
administration of neoadjuvant therapy with RAP-041 to mice
harboring advanced disease, the rate of metastatic dissemination
to the liver decreased by 86% compared with treatment with
control IgG (Fig. 1F). In sharp contrast with anti-VEGF therapy,
which induced an increased rate of metastasis (14, 16), ALK1
inhibition caused regression of preformed hepatic NET foci dur-
ing the course of the therapeutic trial in RIP-TAg2 mice from an
average of 8.1 to 2.8 foci per histologic section (Fig. 1F). In line
with the substantial reduction in both primary tumor burden and
metastatic manifestation in RIP-TAg2 mice following ALK1 inhi-
bition, the rate of OS at 16 weeks of age was also increased from
27% (11/41) to 79% (11/14; Fig. 1G).

ALK1-Fc reduces metastatic dissemination to the lung in a
genetically engineered mouse model of breast cancer
Given the failure of anti-VEGF therapy to affect OS in breast
cancer, we extended our analyses on the role of ALK1 signaling in

Figure 2.
Inhibition of ALK1 reduces the growth, angiogenic response, and metastatic dissemination of early-stage experimental breast cancer. A, MMTV-PyMT mice treated for 4 weeks with twice-weekly administration of control IgG (n = 15) or RAP-041 (ALK1-Fc; n = 15) beginning at 8 weeks of age; *, P < 0.05; **, P < 0.001. B, visualization of endothelial cells in tumors from MMTV-PyMT mice using immunostaining for CD31 (red) counterstained for cell nuclei (blue; DAPI). C, quantitation of vessel area in tumors from MMTV-PyMT mice. Each analysis was performed by assessing >15 images/mouse in at least 5 mice per group. D, assessment of the grade of primary tumors from MMTV-PyMT mice. The percentage of the total lesion area that displays each grade is depicted. Quantitation represents the average of 5 mice per group; *, P < 0.05; χ2-test. E, representative image of pulmonary metastatic lesion from MMTV-PyMT mice, as demonstrated by H&E staining (top) and immunostaining for the oncogene PyMT (bottom). F, quantitation of the number of metastatic foci in the lungs of MMTV-PyMT mice. Analysis was performed on 20 images/mouse in at least 5 mice per group.
metastatic dissemination to this disease by studying the MMTV-PyMT genetically engineered mouse model of mammary carcinoma; a mouse model faithfully recapitulating many aspects of the human disease, including dissemination pattern to the lung and lymph nodes (23). Initial characterization of mammary tumors from MMTV-PyMT mice demonstrated an endothelial cell–exclusive expression of ALK1 and readily detectable expression levels of its ligands BMP9, BMP10, and TGF-β (Supplementary Fig. S1A–S1C). Next, MMTV-PyMT mice were administered RAP-041 from 8 to 12 weeks of age in a preclinical neoadjuvant trial. Consistent with the effects in pancreatic NETs, inhibition of ALK1 significantly delayed the growth and reduced the vessel area of primary mammary carcinomas (Fig. 2A–C). The observed action of RAP-041 was a result of on-target effects, as demonstrated by diminished expression of the ALK1 target genes Id1 and Id3 in tumor lysates (Supplementary Fig. S2A and S2B). Treatment with RAP-041 had no discernible direct effect on the proliferation or apoptosis of malignant cells isolated from MMTV-PyMT tumors in vitro (Supplementary Fig. S2C and S2D), indicating that the therapeutic benefit was derived from indirect targeting of tumor cells by impinging on the neoangiogenic process. Notably, treatment with ALK1-Fc impedes the tumor progression pathway, as evidenced by a shift in the tumor grade from predominant malignant and invasive lesions observed in the control group (31% late carcinoma vs. 18% normal/hyperplasia/adenoma) to a higher degree of premalignant lesions in the treated group (6% late carcinoma vs. 40% normal/hyperplasia/adenoma, Fig. 2D). Importantly, the impaired tumor progression also translated into an 87% decrease in metastatic colonization of the lung (Fig. 2E and F). Tumor growth rate and vessel area were similarly compromised following neoadjuvant treatment with ALK1-Fc of older MMTV-PyMT mice already presenting with fully established disease (Fig. 3A–C). Again, inhibition of ALK1 expressed solely by the tumor endothelium significantly reduced the rate of metastasis by 55% (Fig. 3D and E). Furthermore, in addition to reducing the number of metastatic foci, RAP-041 treatment also significantly moderated the average size of the pulmonary metastatic lesions (Fig. 3F).

ALK1 inhibition induces angiogenic and metastatic blockade in experimental mammary carcinoma

To corroborate our findings of a role for endothelial ALK1 signaling in the metastatic cascade in breast tumors, we transplanted the ER-expressing mouse mammary carcinoma cell line EO771 orthotopically into the mammary fat pad of mice. The expression of BMP9 and TGF-β in EO771 tumor tissue was confirmed by quantitative PCR or immunostaining (Supplementary Fig. S1B and S1C). Consistent with our previous observations, administration of ALK1-Fc significantly delayed the growth of EO771 tumors (Fig. 3G) with concomitant reduction of vessel area (Fig. 3H and I). Importantly, neoadjuvant treatment of EO771-bearing mice with RAP-041 reduced the metastatic success rate to the lung by 87% (Fig. 3J), further demonstrating the involvement of ALK1 ligands and the tumor endothelium in the process of tumor cell dissemination to distant sites.

A combined therapeutic regimen of ALK1-Fc and docetaxel reduces tumor growth and metastatic dissemination

Neoadjuvant therapy of breast cancer is increasingly being used in order to reduce the primary tumor bulk, enable breast-conserving surgery and prevent metastatic manifestation (1). Therefore, we investigated the utility of combining inhibition of ALK1 with commonly used pharmacologic treatment strategies for breast cancer in a series of preclinical trials enrolling MMTV-PyMT mice in the neoadjuvant setting. Combined administration of RAP-041 with trastuzumab or the VEGFR2-neutralizing antibody DC101 did not yield any, or only marginal, therapeutic benefit compared with either treatment alone (data not shown). Strikingly, however, concomitant inhibition of ALK1 with neoadjuvant docetaxel gave rise to improved control of tumor growth (Fig. 4A). The addition of RAP-041 to the docetaxel regimen resulted in partial responses in 5 of 13 (38%) mice, compared with 0 of 10 (0%) in mice treated with single-agent docetaxel (Fig. 4B). Interestingly, treatment with single-agent docetaxel afforded a significant reduction of tumor vascularity; an effect that was exacerbated by combination treatment with RAP-041 (Fig. 4C and D). Most notably, the combination of ALK1-Fc and chemotherapy brought about a further 63% decrease in the metastatic index of the lung compared with docetaxel alone and prevented pulmonary metastases in 93% compared with control therapy (Fig. 4E).

ALK1 is an independent biomarker for metastatic recurrence of human breast cancer

Comparative studies demonstrated widespread expression of BMP9 protein, but not BMP10 protein, by malignant cells in human breast carcinomas (Fig. 5A). Functionality of the ALK1 paracrine signaling network and therapeutic utility of ALK1-Fc in the human setting was demonstrated by near-complete retardation of the growth of orthotopic xenografts of the aggressive triple-negative human breast carcinoma cell line MDA-MB-231 by treatment with ACE-041/dalantercept (the human counterpart of RAP-041; Fig. 5B). Next, to explore whether the expression of ALK1 (gene name ACVRL1) holds prognostic capability for metastatic disease in human patients, we analyzed gene-expression patterns in tumor material from a population-based nested case–control study encompassing 768 subjects with complete clinical follow-up (21). Briefly, 190 breast cancer patients that developed distant metastatic disease (cases) were selected from a consecutive
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series of individuals and three random control patients (free from metastasis) for each case were closely matched by adjuvant therapy, age and calendar period at diagnosis (21). Expression of ACVRL1 was found to correlate significantly with prototypical endothelial cell genes, further corroborating the predominant vascular expression of ALK1 in human breast cancers (Supplementary Table S1). In addition, ACVRL1 expression was significantly correlated to the expression of its target gene Id1, implying activation of the pathway (data not shown). In strong support of our functional data, abundant expression of ACVRL1 was highly significantly associated with the incidence of metastatic disease (Table 1). Similarly, expression of SMAD6, a known downstream target gene of ALK1 activation was linked to recurrent disease (Table 1). In sharp contrast, the expression of the canonical TGFβ type I receptor ALK5 (TGFBRI) and its ligands TGFβ1,2 that are implicated in promotion of metastasis through induction of epithelial-to-mesenchymal transition (EMT), was equally distributed between cases and controls, with the exception of TGFβ1, expression of which was marginally associated with metastatic disease (Table 1). Importantly, in a multivariate analysis of risk factors for presenting with metastatic disease, expression of both ACVRL1 (HR, 3.59; 95% CI, 2.52–5.15) and SMAD6 (HR, 1.43; 95% CI, 1.15–1.77) remained as statistically significant and independent prognostic factors, alongside well-known clinical risk factors such as lymph node status, tumor size, and HER2 amplification (Table 1). Intriguingly, the known ligands for ALK1, that is, BMP9 (GDF2) and BMP10, were only weakly associated to metastasis, even when their expression was combined (Table 1).

High expression of endothelial ALK1 is an independent prognostic factor for poor survival in human breast cancer

To further validate our finding of a functional association between ALK1 signaling and metastatic colonization in human breast cancer, we analyzed breast cancer gene-expression data from TCGA. The validation set revealed that expression of ACVRL1 was indeed correlated with the expression of well-known endothelial markers (Supplementary Table S1). Next, a Cox proportional hazards model was applied to gene-expression data from TCGA with event-free survival as the endpoint. Univariate models did not demonstrate any significant prognostic information held by either ACVRL1 itself (data not shown) or by a general vascular index (normalized average expression of the prototypical endothelial cell markers PECAM1, CD31, and CD34; hereafter referred to as the endothelial metagene). Strikingly, however, in a multivariate model (Table 2), both the ACVRL1 expression level (HR, 2.35; 95% CI, 1.34–4.09) and the endothelial metagene (HR, 0.46; 95% CI, 0.28–0.74) were independent prognostic factors for event-free survival, also after adjustment for lymph node status and stratification for the molecular subtype of the disease according to the PAM50 profile. The opposing HRs of the vascular index and the ACVRL1 expression level in this dataset suggested that the
Table 1. Univariate and multivariable conditional logistic regression models comparing patients developing metastatic disease with patients free from disseminating disease in a nested case-control study*

<table>
<thead>
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<th>Variable</th>
<th>Univariate models</th>
<th>Multivariable model A</th>
<th>Multivariable model B</th>
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<tr>
<td></td>
<td>n</td>
<td>HR* (95% CI)</td>
<td>P</td>
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<tr>
<td>ACVRL1 (ALK1)</td>
<td>1.92 (1.58–2.34)</td>
<td>&lt;0.001</td>
<td>3.59 (2.51–5.15)</td>
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<td>Endothelial metagene</td>
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<td>ACVRL1:endothelial metagene index*</td>
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<td>2.01 (1.62–2.50)</td>
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<td>GDF2 (BMP9)</td>
<td>1.11 (0.95–1.30)</td>
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<td>BMP10</td>
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<td>ALK1 ligands [GDF2 (BMP9) + BMP10]</td>
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<td>SMAD6</td>
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<td>&lt;0.001</td>
<td>1.43 (1.15–1.77)</td>
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<td>TGFBRI1 (ALK5)</td>
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<td>0.75 (0.44–1.31)</td>
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Abbreviation: ref, reference.

*Controls randomly matched to cases by age, adjuvant therapy, and calendar period at diagnosis.

**Numerical variables are centered and scaled (SD set to one) in the models. Gene-expression values are normalized log2 summarized microarray probe intensity values.

For numerical variables, HR is the relative hazard when increasing the variable one SD.

Average expression of the prototypical endothelial cell markers PECAM1, CDH5, and CD34.

Differences in ACVRL1 expression and endothelial metagene expression; corresponds to (log2 of the ratio of ACVRL1 probe intensity over average endothelial metagene probe intensity.

**molecular characteristics, rather than the absolute extent of vascularization, hold prognostic information. The ratio between ACVRL1 expression and the endothelial metagene (i.e., the relative expression of ACVRL1 per endothelial cell) was, therefore, evaluated and found to serve as a highly specific prognostic biomarker for recurrent disease; breast cancer patients within the quartile of highest ACVRL1:endothelial metagene ratio were subject to an exceedingly poor event-free survival, compared with those patients with the lowest ratio (Fig. 5C). Reassuringly, the independent prognostic capability of the ACVRL1:endothelial metagene ratio was confirmed by analysis of gene-expression data from the nested case-control study (Table 1). Further analysis revealed that the association between the ACVRL1:endothelial metagene index and distant metastases was robust regardless of treatment received and was not a feature of any particular molecular subtype or size of breast tumor (Supplementary Fig. S3A–S3C).

**Discussion**

Taken together, we have combined mechanism-based studies of ALK1 signaling in advanced genetically engineered mouse models of breast cancer with preclinical efficacy trials of a clinically tractable pharmacologic inhibitor of ALK1 and expression analysis of ACVRL1 in human patient materials in relation to relevant clinical parameters for metastatic disease. The present studies strongly suggest an independent role for endothelial ALK1 signaling in the process of metastatic dissemination and colonization of distant organs in breast cancer. On the basis of our findings, pharmacologic inhibitors of the ALK1 pathway, thus, present as attractive and realistic partners with chemotherapy in the management of metastatic breast cancer.

ALK1-blocking agents are currently being developed clinically for various malignancies (17). Dalantercept (ACE-041), the human counterpart of RAP-041, is an ALK1 ligand trap comprising the extracellular domain of ALK1 fused to the Fc portion of IgG. Phase I clinical trials demonstrate the safety and tolerability of dalantercept; the most common and dose-limiting side effects include peripheral edema and fluid retention (24). Likewise, the fully human ALK1-neutralizing antibody PF-03446962 has concluded phase I clinical trials with grade 3 thrombocytopenia and increase in pancreatic enzymes as the dose-limiting toxicities (25). Both compounds show evidence for on-target effects on the ALK1 targeting agents is as distinct from that of anti-VEGF compounds, such as bevacizumab, sunitinib, and sorafenib, indicating a unique mechanism of action. In our preclinical trials, we found that, unlike VEGF pathway inhibitors, prolonged administration of ALK1-Fc did not give rise to widespread tissue hypoxia, rebound of tumor growth, increased local invasion or augmented seeding of distant...
metastases (14–16, 26). In sharp contrast, neutralization of ALK1 ligands in the neoadjuvant setting resulted in a substantial reduction in metastatic colonization and in some cases even regression of preexisting metastatic lesions. It is interesting to note that the ALK1 target gene Id1, which we found to be substantially downregulated following treatment with RAP-041 and significantly correlated to ALK1 expression in human breast tumors, is part of a gene-expression signature predictive of breast cancer lung metastasis (27) and suppression of Id1 impairs metastatic colonization in a mouse model of lung carcinoma (28). The fact that ALK1 inhibition did not provoke tissue hypoxia is the most likely cause for the observed discrepancy with anti-VEGF therapy, as hypoxia has been suggested to be the main driving force for the malignization of tumors following VEGF blockade in preclinical studies (14, 26). The relative lack of hypoxia, despite reduced vessel area, implicitly suggests that ALK1 inhibition improves the exchange of oxygen and nutrients across the abnormal neovasculature in tumors. Further mechanistic studies of the distinct effects of ALK1-Fc on the tumor vasculature are warranted.

Herein, we provide compelling evidence from a population-based nested case–control study encompassing 768 subjects (23) that high expression of ACVRL1 in the tumor vasculature serves as a highly significant biomarker for a metastatic phenotype in breast cancer, alongside traditional risk factors such as lymph node status, tumor size and HER2 amplification. This finding was corroborated by analysis of the independent TCGA dataset, in which the expression of endothelial ACVRL1 was found to be strongly associated with event-free survival. Our findings should be confirmed at the protein level, but we have been unable to do so in the current study despite substantial efforts, due to a lack of specific reagents to detect the ALK1 protein in human tissues (data not shown). Intriguingly, ALK1 expression was closely linked to prototypical endothelial cell marker genes, providing further evidence that the endothelium takes an active part as a key regulator of the metastatic process; an aspect of the vascular wall that has been highlighted also in recent studies of signaling pathways emanating from endoglin, CCL2/CCR2 and HIF1α/2α in the tumor endothelium (16, 29, 30). Signaling by TGFβ in malignant cells promotes many aspects of the metastatic process, most notably migration and invasion, through induction of EMT (31). We recently demonstrated that the action of TGFβ on the vasculature weakens the endothelial cell barrier to tumor cell intravasation, thus endorsing malignant cell escape from the primary site into the bloodstream through an analogous mesenchymal transition of endothelial cells (16). Hence, the mechanism behind the antimetastatic effect of single-agent ALK1-Fc conceivably involves sealing the endothelial cell barrier to cancer cell transmigration, thereby confining malignant cells within the primary tumor. Furthermore, combined neoadjuvant treatment with RAP-041 and docetaxel eradicated the vast majority of pulmonary metastases. Docetaxel treatment gives rise to a well-documented reduction in vessel area (32), and the synergistic interaction with ALK1 inhibition is, thus, likely to take place at the level of the tumor endothelium.

Taken together, our mechanism-based therapeutic studies, combined with gene-expression analysis of patient specimens designed to investigate prometastatic factors, thus strongly support further development of ALK1-targeting agents, such as dalantercept and PF-03446962, as clinically tractable combination partners for chemotherapy to reduce the incidence of distant metastases in breast cancer.

Disclosure of Potential Conflicts of Interest

R. Kumar is a Chief Scientific Officer and has ownership interest (including patents) in Acceleron Pharma. K. Pietras has ownership interest in a patent pertaining to ALK1 antagonism held by the Ludwig Institute for Cancer Research Ltd and licensed to Acceleron Pharma. No potential conflicts of interest were disclosed by the other authors.

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