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INTRODUCTION: It is unknown what specific biochemical and biological mechanisms control metastasis. We pursued the work proposed in this application because it is our assertion that uncovering the mechanism(s) responsible for regulating metastatic colonization in ovarian requires a fresh look from a new perspective. To this end we formulated and began to test a completely novel hypothesis: That a Quorum Sensing mechanism is involved in metastatic colonization. Quorum Sensing is a process of cell-cell communication that bacteria use to control gene expression in response to fluctuations in cell population density. Quorum Sensing involves production of and response to the accumulation of a critical concentration of extracellular signal molecules. This mechanism allows bacteria to act as individuals and participate in group activities. Of relevance to metastasis is the finding that pathogenic bacteria can sense and integrate information about their numbers (quorum), physical interactions with host cells, and host-derived stress cytokines. When certain bacteria sense host vulnerability and have sufficient cell density, they initiate a coordinated attack by expressing virulence genes and forming organized, stable biofilms [i.e. complex, heterogeneous communities of cells within an extracellular matrix attached to a solid surface] which exacerbate disease and are refractory to a battery of therapies. This process is analogous to metastatic colonization in ovarian cancer: cells migrate toward/on target surfaces (organ-specific homing), show cell-cell and cell-matrix interactions (tumor cell-stromal cell crosstalk), remain subclinical until they can mount an effective attack (dormancy), form complex structures with channels for nutrient flow (vascularized lesions), and contain resistant cells which can cause disease recurrence (persistors). Our hypothesis predicts that groups of cancer cells can communicate through quorum sensing-like mechanisms, initiating a program of gene expression which confers cellular changes required for efficient metastatic colonization. These cells for overt metastases, while cells that cannot form quora do not. To test this, our proposal employed a combination of experimental approaches drawn from the disciplines of experimental metastasis research and bacterial quorum sensing studies.

BODY: The proposed studies and progress toward each aspect of the work outlined in the statement of work in the application are described in the following sections. Accomplishments as well as technical challenges are described.

Specific Aim 1. To identify the quorum-dependent step(s) of metastatic colonization by SKOV3ip.1 cells. At the time of the initial submission we had preliminary data which suggested that cells which express the MKK4 metastasis suppressor protein are less efficient at completing an early step(s) of metastatic colonization. We put forth a hypothetical model of metastatic colonization that was included in the project proposal (Figure 1). We proposed that we could identify the quorum-dependent step(s) using imaging and quantitative techniques. The long term goal is the use this information to develop *in vitro* assays that model specific *in vivo* processes. Examples of *in vitro* assays which potentially could be used to model specific steps in metastatic colonization are shown in Figure 1 (lower panel).

Hypothesis/Approach*:* We hypothesized that a quorum of cells grown at optimal density can proceed efficiently through steps of metastatic colonization, while suboptimal number of cells grown at low-density, or MKK4-expressing cells cannot. We predicted that ectopic expression of MKK4 in SKOV3ip.1 cells has the same effect as reducing the density of the cells in the **Y ~*ƒ*(N,d)t.** In this function Y is the yield of metastases after a given time (t) after injection of a specific number of cells (N) grown at a specific density (d). We proposed that MKK4 affects a quorum-dependent behavior of SKOV3ip.1 cells. To test this hypothesis, we first need to 1) establish the minimum number, or quora, of high-density SKOV3ip.1 cells necessary to form ~20 overt metastases at 20 dpi; 2) define "low-density" and 3) identify the step(s) in metastatic colonization where low-density cells persist; the quorum-dependent step. We can use these parameters to test what effect MKK4's signaling cascade has on this process.

Progress on Aim 1

Determining the minimum number of high-density SKOV3.ip.1 cells needed for efficient metastatic colonization and the effect of cell density on metastatic colonzation.

Determination of the rate-limiting step of metastatic colonization and the effect that MKK4 has on quorum-dependent functions of SKOV3ip.1 cells.

Specific Aim 1. To identify the quorum-dependent step(s) of metastatic colonization by SKOV3ip.1 cells.

Experiment 1: Determining the minimum number of high-density SKOV3.ip.1 cells needed for efficient metastatic colonization. In order to complete this study we first had to derive a series of SKOV3ip.1 cells that express red fluorescent protein (RFP). Cells were transfected with the appropriate expression construct, expression was confirmed in the stably expressing cells, and cells with high expression of the RFP protein were selected by FACS. The *in vivo* behavior of the SKOV3ip.1-pLNCX2RFP cells was confirmed to control for any untoward effects of the cell-tagging process.

The minimum number, or quorum, of high-density [80% (4.0×10^5 cells/cm^2)] SKOV3ip.1-pLNCX2-RFP cells necessary to yield approximately 20 1 mm diameter metastases was determined empirically. The number of over metastases formed by injection of 1×10^6, 1 x 105, 1×10^4, or 1×10^3 SKOV3ip.1-pLNCX2-RFP cells at 20 days post injection was quantified. As predicted there was a sharp drop-off in the yield of metastases formed by decreasing numbers of cells. We had predicted that this drop-off would be at 1 x 104 cells; however our study found that it was actually 1×10^5 cells. Additional metastasis assays using increments of high-density cells between 1×10^6 and 1×10^5 cells were used to

further define the number of cells constituting the quorum. These addition studies found that the threshold quorum of cells at 85% confluence was 1 x 10^6. In subsequent studies we found that the density of the cells in culture at the time of harvest for injection did have a significant effect on their proliferative capacity. Specifically, SKOV3ip.1-pLNCX2-RFP cells were plated at 85% (4.0 x 10^5 cells/cm^2), 70% (3.2 x 10^5 cells/cm^2), 50% (2.3 x 10^5 cells/cm^2), and 20% (0.9 x 10^5 cells/cm^2) confluence.

Experiment 2: Determining the minimum density of SKOV3ip.1 cells needed for efficient metastatic colonization. As we suspected at low density there a significant decrease in proliferative capacity and thus the ability of cells to complete colonization. Expression of MKK4 increased the magnitude of this effect, which is consistent with the global hypothesis of this work.

Experiment 3: Determining the rate-limiting step of metastatic colonization. To determine which step in metastatic colonization is quorum dependent, we first analyzed the number and distribution of cells attached to the omentum. In a pilot study by Hickson, fluorescently–labeled SKOV3ip.1 cells could be found attached to the omentum, a predominant site for experimental metastases, within minutes after injection. The localization could mimic an early step in omental caking, and further demonstrates the utility of this model.

To begin these studies we focused on defining the rate-limiting steps of the experimentally determined quorum of cells at high-density. We compared the SKOV3ip.1-vector only controls with the SKOV3ip.1-HA-MKK4 cells to further define the aspect of metastatic colonization affected by MKK4 activity. Based upon our cumulative experience, we have delineated this process into four general steps: 1) motility toward and attachment to target structures, 2) survival/proliferation/distribution on the target organ, 3) formation of microcolonies or aggregates, and 4) proliferation into overt metastases. We determined the time points for each of these studies empirically. As we had proposed the number of cells that attach to the omentum were accurately quantitated by real time quantitative PCR. We had more difficulty that anticipated in developing appropriate imaging methods to quantitate the distribution of cells on the omentum, this will take further refinement. It may be possible to accomplish this using an improved fluorescent protein, mCherry, and a new imaging modality the Olympus OV-100 fluorescent imaging system, recently procured by our Institution. Neither of these resources were widely available at the time we proposed this work.

Experiment 4: Determining the effect that MKK4 has on the quorum-dependent functions of SKOV3ip.1 cells. We successfully determined that quorum-dependent function of MKK4 in SKOV3ip.1 cells is the induction of a reversible cell cycle arrest of cells at the metastatic site. That work is published in two separate papers by Lotan *et al* (Cancer Res. 2008 Apr 1;68(7):2166-75) and Hickson *et al* (Clin Exp Metastasis. 2008 May 31. [Epub ahead of print]). The relevant data is published within those papers.

Specific Aim 2. To test whether SKOV3ip.1 cells produce and respond to quorum sensing autoinducers.

Experiment 1: Determining the ability of conditioned media prepared from high-density cells to induce quorum sensing behavior in low-density cells.

Experiment 2: Determining the ability of SKOV3ip.1-HA-MKK4 cells to make and respond to secreted autoinducers.

Our published studies cited above found that the approach that we originally proposed in the application was not sufficient to autoinducer-type activity. Once we determined that the quorum-dependent event occurred early in the timecourse of metastatic colonization, we attempted to use the conditioned media treatments to affect cell proliferation in vitro. However these attempts were unsuccessful. This work has to be revisited with the new data that we are accumulating on MKK4's affects on metastatic colonization. In vivo metastasis assays may be too complex and long-term to measure quorum-dependent functions.

Specific Aim 3. To test known quorum sensing signaling molecules for new functions in the induction of quorum sensing-like behavior.

Experiment 1: Determining the ability of known bacteria autoinducers to induce quorum sensing behavior in SKOV3ip.1 cells.

Experiment 2: Determining the ability of bacterial cells to respond to autoinducers secreted by SKOV3ip.1 cells.

Since we could not get Aim 2 to work Aim 3 was not feasible. We need an in vitro assay and were unable to develop anything promising.

KEY RESEARCH ACCOMPLISHMENTS:

- Identified a novel quorum-dependnet effect of MKK4 in SKOV3ip.1 cells
- Published our quorum-sensing hypothesis in a journal highly read by the metastasis community
- Secured a session dedicated to quorum sensing at the 2008 Metastasis Research Society-American Association for Cancer Research Joint Meeting (August 2008) http://www.aacr.org/home/scientists/meetings--workshops/special-conferences/joint-metastasis-research-society-aacr-conference-on-metastasis.aspx

REPORTABLE OUTCOMES: Provide a list of reportable outcomes that have resulted from this research to include:

Hickson J, Diane Yamada S, Berger J, Alverdy J, O'Keefe J, Bassler B, Rinker-Schaeffer C. Societal interactions in ovarian cancer metastasis: a quorum-sensing hypothesis. Clin Exp Metastasis. 2008 May 31. [Epub ahead of print]
Lotan T, Hickson J, Souris J, Huo D, Taylor J, Li T, Otto K, Yamada SD, Macleod K, Rinker-Schaeffer CW. c-Jun NH2-terminal kinase activating kinase 1/mitogen-activated protein kinase kinase 4-mediated inhibition of SKOV3ip.1 ovarian cancer metastasis involves growth arrest and p21 up-regulation. Cancer Res. 2008 Apr 1;68(7):2166-75.

CONCLUSION: We are pleased with the progress we made with the time and funds available. In retrospect we were overly optimistic in our experimental design. None-the-less we have gotten the attention of both the metastasis research and bacterial research communities. The dialogues and interest this has stirred is making an impact. Further we will continue to pursue this work, although it may take years to accomplish. This is a big idea and it will take time. We are very grateful to the DOD for early funding of this work.

APPENDICES: the two manuscripts listed above are attached.

Clin Exp Metastasis
DOI 10.1007/s10585-008-9177-z

REVIEW

Societal interactions in ovarian cancer metastasis: a quorum-sensing hypothesis

Jonathan Hickson · S. Diane Yamada · Jonathan Berger · John Alverdy · James O'Keefe · Bonnie Bassler · Carrie Rinker-Schaeffer

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Abstract The biochemical and biological mechanisms metastatic cancer cells use to function as communities and thwart internal and external growth control mechanisms remain undefined. In this work, we present the hypothesis that cancer cells may use a *Quorum-Sensing* mechanism to regulate multicellular functions and control steps in metastatic colonization. Quorum sensing is a bacterial cell-cell communication process used to track increasing cell-population density and, in response to changes in cell number, coordinate gene expression and behavior on a community-wide scale. Important parallels between the behavior of societies of bacterial cells and societies of malignant cancer cells exist in the bacterial literature. Of relevance to metastasis is the finding that pathogenic bacteria use quorum sensing to determine when their population numbers are high enough to collectively form biofilms in or on host organisms. Biofilms are complex, heterogeneous communities of bacterial cells encased within an extracellular matrix attached to a solid surface. Biofilms exacerbate disease and are refractory to a battery of therapies. We suggest that the quorum-sensing-controlled bacterial biofilm formation process closely parallels the steps in metastatic colonization. Cells migrate toward/on target surfaces (organ-specific homing), show cell-cell and cell-matrix interactions (tumor cell-stromal cell crosstalk), remain subclinical until they can mount an effective attack (dormancy), form complex structures with channels for nutrient flow (vascularized lesions), and contain resistant cells which can cause disease recurrence (persistors). Using ovarian cancer as an example, we present data supporting the connection between metastatic colonization and quorum sensing and discuss the implications for understanding and controlling metastasis formation.

Keywords Metastatic colonization · Ovarian cancer · Quorum sensing

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Abbreviations

d	Density of cells injected
dpi	Days post injection
EPS	Extracellular polysaccharide substance
HA	Hemagglutinin
JNK	c-Jun NH_2 terminal protein kinase
MAPK	Mitogen-activate protein kinase
MKK4/SEK1	Mitogen-activated protein kinase kinase 4/stress-activated protein/Erk kinase 1

MKK4-KR	Mitogen-activated protein kinase kinase 4-kinase inactive
N	Number of cells injected
PCR	Polymerase chain reaction
SAPK	Stress-activated protein kinase
SCID	Severe combined immunodeficient
t	Length of experiment
Y	Yield of experimental metastases

Introduction

In 2008, more than 565,000 deaths from cancer are projected to occur in the United States, most of them from metastatic disease [1]. Metastases are not a direct extension of the primary tumor and are not dependent upon the route of spread (i.e. hematogenous versus lymphatic versus peritoneal dissemination) [2]. Rather, metastasis is defined as dissemination of neoplastic cells from a primary tumor to discontinuous nearby or distant secondary sites where cells proliferate to form overt masses. Of particular interest and clinical relevance is the high recurrence rate in many cancer types after "definitive" therapies such as surgery, radiotherapy, or chemotherapy, demonstrating the urgent need to both identify patients at risk for disease recurrence as well as to develop therapies that specifically target the metastatic process. This discussion will focus on ovarian cancer, although we believe that many of the points presented will apply to other malignancies.

Since the majority of patients with ovarian cancer present with extensive intraperitoneal metastases, it has been difficult to glean information on the natural history of the disease. For the most part, steps in ovarian cancer metastasis have been logically inferred using data from studies of in vitro assays, experimental metastasis assays, and analogies to hematologic metastasis. These observations suggest that cells acquire metastatic competence and are able to survive detachment from the primary tumor, turbulent flow, and exposure to cytokines during transport by the peritoneal fluid. It is also likely that increased motility of cells toward chemical gradients, and physical and biochemical interactions facilitate adherence of cells to secondary sites. Based on patterns of clinical metastases, it is postulated that ovarian cancer cells preferentially adhere to the liver, small bowel, and omentum. Adherent cells that survive and initiate growth can complete the process of metastatic colonization and form detectable overt masses.

The prevailing view is that ovarian cancer metastasis is an inevitable outcome of tumorigenesis and primary tumor growth and is regulated by the same genetic events. However, numerous studies utilizing multiple neoplasms suggest that the process of metastasis is actually regulated by distinct molecular phenomena [3–6] To date, twenty metastasis suppressors have been identified that specifically regulate metastasis formation *without* affecting primary tumor growth *in vivo* and/or are specifically able to inhibit metastatic colonization [5]. Studies of metastasis suppressor proteins are providing insights into this clinically important process [4, 5]. A focus of our laboratory is discerning the mechanism(s) by which metastasis-suppressors impair metastasis formation and how cells may eventually overcome these effects. Over the past decade, we have made several unanticipated findings prompting the metastasis-quorum-sensing hypotheses put forward in this perspective piece. Quorum sensing is a mechanism used by bacterial populations which enables them to adapt to ever-changing environments and carry out complex behaviors. Quorum sensing enables bacteria to communicate, self-organize into cooperative groups, and carry out processes that are successful only because a critical number of cells carry them out in synchrony. The following sections provide specific examples of recent data that prompted the formulation of our quorum sensing hypothesis, a comparison of quorum sensing and metastatic colonization, and examples from the greater literature on metastasis that support a quorum sensing mechanism.

MKK4: a map kinase kinase that functions as a metastasis suppressor

As a key member of the stress-activated protein kinase (SAPK) signaling cascade, MKK4 can phosphorylate both the JNK and p38 MAPKs, resulting in the activation of transcription factors and/or phosphorylation of other regulatory proteins [7]. Using SKOV3ip.1 cells, a metastatic human ovarian cancer cell line that lacks significant endogenous MKK4, we showed that ectopic expression of hemagglutinin (HA)-tagged MKK4 reduces overt experimental metastasis formation by 90% in a kinase-dependent manner, and that MKK4 signals through p38, and not JNK, to suppress in vivo metastatic colonization [8, 9]. As is the case with other metastasis suppressors, SKOV3ip.1 cells expressing HA-MKK4 have no detectable alterations in growth rate or apoptosis under a variety of in vitro growth conditions [8]. Thus, the suppressive effect of MKK4 on metastatic growth is dependent on in vivo activity of the protein. Interestingly, animals injected with MKK4-expressing cells show a 70% improvement in survival as compared to controls, but these animals will eventually succumb to disease burden [8, 9].

The above findings raised some important questions. What are the biological mechanisms responsible for MKK4-mediated suppression of metastatic colonization? Can MKK4-expressing cells become resistant to MKK4's

effects? As described in the following sections, we conducted studies designed to examine how MKK4-expressing cells ultimately bypass MKK4-mediated suppression. What was especially puzzling was that MKK4's ability to block metastasis appears to be dependent on cell number. To our knowledge, no other study has examined the effect of cell number on metastasis suppressor function. Further, in recent years there have been very few studies investigating the potential role of cell number on metastatic efficiency or other hallmark behaviors of metastatic cells. Therefore, our goal was to formulate a testable hypothesis regarding cell number and interactions with the host microenvironment that would be supported by the metastasis literature and our data regarding the mechanism by which MKK4-suppressed cells can overcome suppression.

Societies of cells can bypass MKK4-mediated suppression of SKOV3ip.1 ovarian cancer metastatic colonization

We have previously demonstrated that expression of HA-MKK4 in SKOV3ip.1 cells significantly reduces the number of overt implants following intraperitoneal injection and extends animal survival [8, 9]. Eventually, however, even mice injected with HA-MKK4-expressing cells develop macroscopic metastases and succumb to their disease burden. Recently published studies from our laboratory examined the biological mechanism of MKK4-mediated metastasis suppression and eventual outgrowth of cells. Specifically, using an in vivo time course assay, Lotan et al. showed that both vector-only and HA-MKK4-expressing metastases were able to be mathematically modeled using the same Gompertzian equation (Fig. 1, Panel A). The HA-MKK4 growth curve was simply shifted in time relative to the vector-only curve, with metastasis formation delayed by an average of 30 days [10].

These data raise the question of whether the eventual outgrowth of HA-MKK4-expressing cells is the result of selection for variant clones that have lost or inactivated MKK4 or another mechanism such as a population-wide adaptation to the consequences of SAPK signaling [10]. Published data reproduced in Fig. 1, Panel B illustrate that overt metastases arising from HA-MKK4-expressing SKOV3ip.1 cells at $\sim$65 dpi do, in fact, continue to express HA-MKK4, indicating that in vivo selection for deletion or decreased expression of MKK4 has not occurred [10]. To further expand upon these findings, 25 independent metastasis-derived cell lines were established and 100% of them retained expression of HA-MKK4 protein which could be artificially activated in vitro (representative data shown in Fig. 1, Panel C [10]). Compared to vector-only cells, MKK4 metastasis-derived lines remained suppressed in the ability to form overt experimental metastases when re-injected into naïve mice (Fig. 1, Panel D [10]). Taken together, these recently published in vitro and in vivo data strongly suggest that eventual outgrowth of HA-MKK4-expressing cells is not due to selection for clones of cells that have permanently altered their MKK4 signaling status, but rather, is due to adaptation of the population to the biological consequences of SAPK signaling [10].

Bypass of MKK4-mediated suppression is related to size of the metastatic foci and/or population number

We have recently published data showing that HA-MKK4-expressing cells display decreased proliferation as measured by BrdU incorporation and phospho-histone-H3 staining (Fig. 2, [10]). We were intrigued by our observation that a shift from low proliferation to increased proliferation coincides with lesions reaching an area of approximately 10 mm^2 (i.e. Log 4 μm^2; Fig. 2 [10]). We speculated that the number of cells within an HA-MKK4-expressing lesion might be vital to whether MKK4 could exert a suppressive effect. To test this notion we revisited findings from our in vivo time course assay which suggested that once a critical threshold of cells was reached, SKOV3ip.1-HA-MKK4 cells overcome suppression (Fig. 1 Panel A, [10]). We speculated that if suppression was related to the number of cells colonizing the target organ, then increasing the number of cells injected should bypass MKK4-mediated suppression.

Using our standard assay, the metastatic ability of 1×10^6 SKOV3ip.1-vector and SKOV3ip.1-HA-MKK4 cells as well as SKOV3ip.1-HA-MKK4-KR cells, which express a kinase inactive mutant of MKK4 (HA-MKK4-KR), was assessed. The HA-MKK4-KR-expressing cells behave in analogous fashion to vector-only controls since the protein cannot phosphorylate downstream targets. The number of overt metastases in each group was assessed and the average number of metastases per group versus time displayed in Fig. 3. Interestingly, when 1×10^7 SKOV3ip.1-HA-MKK4 cells were injected, we observed metastasis formation similar to that produced by 1×10^6 SKOV3ip.1-vector or SKOV3ip.1-HA-MKK4-KR cells. These previously unpublished in vivo data support the notion that a critical threshold number of SKOV3ip.1 cells can bypass suppression and initiate growth, which prompted several questions. Are there examples of autonomous single-celled organisms that show variable behaviors depending on their cell number? If so, what is the mechanism by which these organisms coordinate and execute functions as a population? Finally, do such multicellular communities

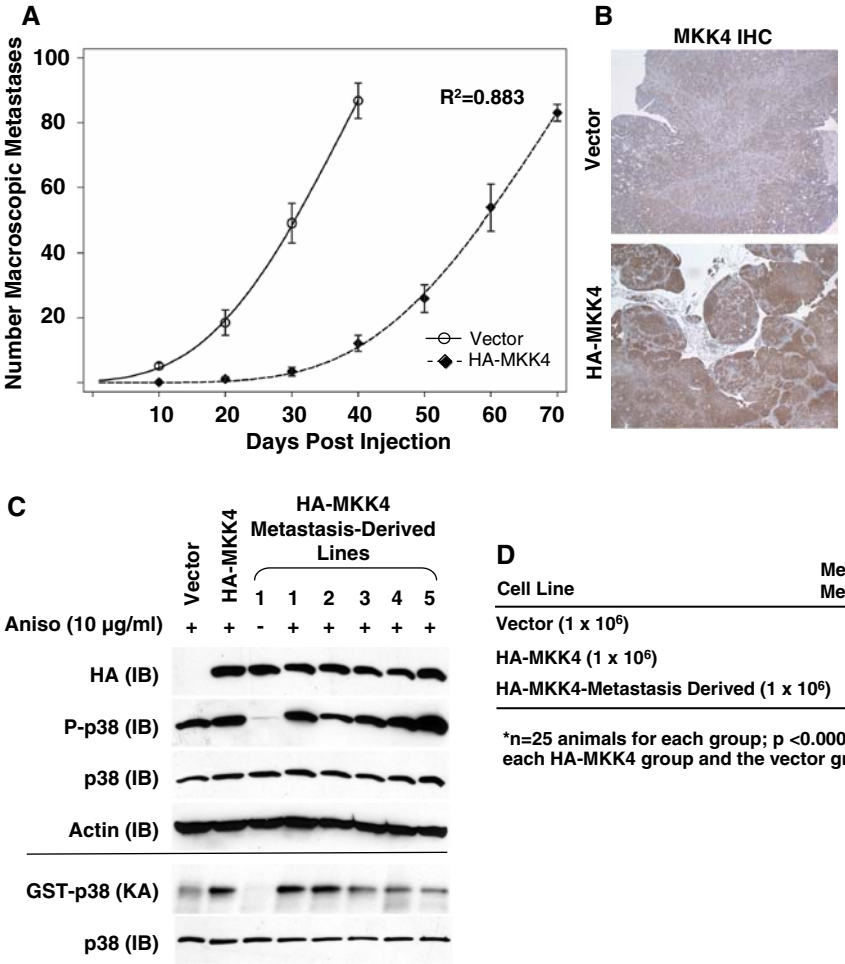

Fig. 1 HA-MKK4-expressing SKOV3ip.1 cell lines derived from macroscopic metastases retain expression of functional MKK4 in vitro and remain suppressed for metastasis when reinjected into naïve mice. (**a**) HA-MKK4-expressing cells are delayed in forming macroscopic metastases. The number of ≥1 mm metastases present as a function of time was determined by injecting SKOV3ip.1-vector (solid line, circles) clones or SKOV3ip.1-HA-MKK4 (dashed line, diamonds) clones using our standard intraperitoneal metastasis assay [10]. Means and standard errors at each time point are presented and represent the data from 12 to 15 mice per timepoint. Nonlinear regression revealed that a 3-parameter Gompertz model fit the 165 data points well ($R^2 = 0.883$), indicating that the shape of the growth curve was similar between the two groups. (**b**) Immunohistochemical staining for MKK4 in macroscopic metastases derived from vector-only and HA-MKK4-expressing at 30 and 65 dpi respectively. SKOV3ip.1 cells have low endogenous MKK4 levels, as seen here in vector-only cells. MKK4 was consistently detected in macroscopic HA-MKK4 metastases. (**c**) Clonal cell lines were derived from 10 independent SKOV3ip.1-HA-MKK4 macroscopic metastases and screened for the presence of the HA-tag, and endogenous phospho-p38, p38, and actin following stimulation with anisomycin (representative data are shown). In vitro kinase assays show that HA-MKK4 is functional in vitro and it phosphorylates the GST-p38 substrate in a manner similar to parental cell line controls (positive control, second lane). As a loading control, the blot was also probed for the GST-p38 substrate (bottom panel). (**d**) All five metastasis derived cell lines in panel *B* were re-injected into 5 mice each for the standard end-point metastasis assay. These cell lines were equally suppressed for macroscopic metastasis formation at 30 dpi compared to parental lines ($P < 0.0001$ for both groups compared to vector control). (This figure was adapted from data originally published by Lotan et al. [10])

exhibit any behaviors that resemble those associated with metastatic cancer cells?

Quorum sensing regulates population-dependent behaviors of bacterial societies

In order to adapt to ever-changing environments and carry out complex behaviors, bacteria have developed the ability to communicate and self-organize into cooperative groups. In a process called *quorum sensing*, populations of bacterial cells function together to carry out processes that are successful only because a critical number of cells carry them out in synchrony [11–13]. Two seminal studies, one in the 1960s [14] and one in the 1970s [15] suggested the concept that bacteria could communicate and act in groups. Prior to this work, bacteria had been viewed as asocial organisms that exhibited only individual behaviors. A

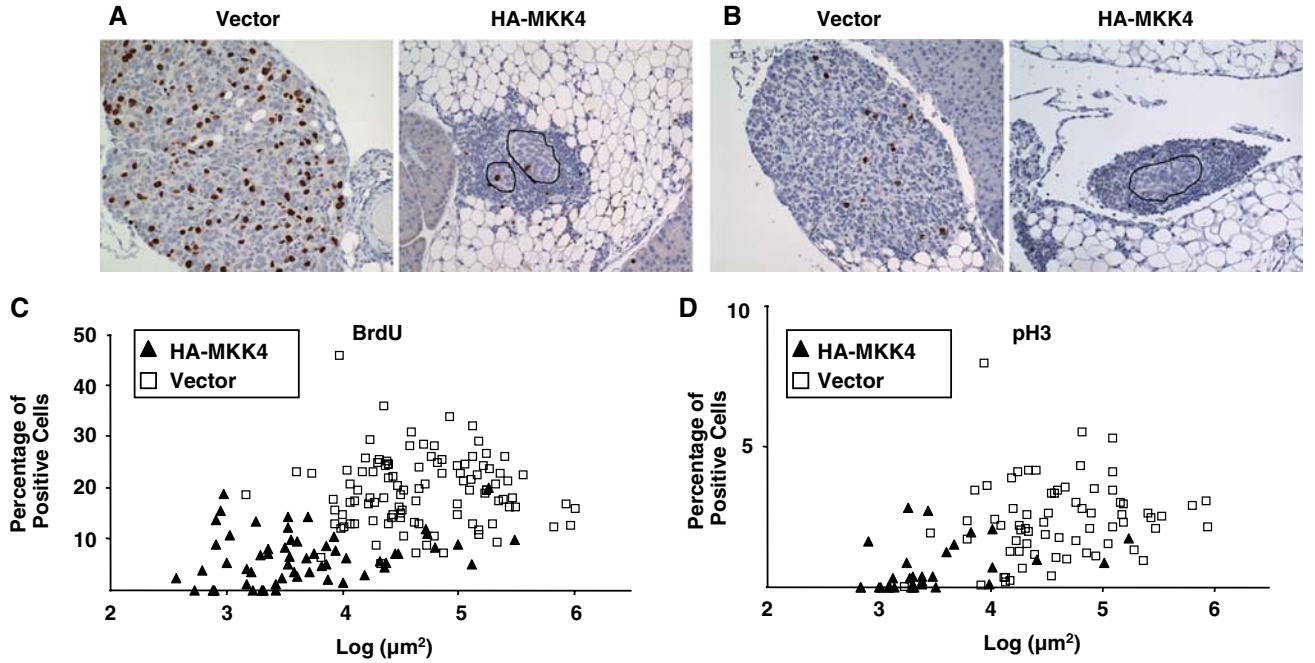

Fig. 2 HA-MKK4-expressing microscopic metastases show decreased proliferation as assessed by BrdU incorporation and pH3 staining at 14 dpi. A. BrdU was injected intraperitoneally 4 h prior to the experimental endpoint. Immunolabeling for BrdU in vector-only and HA-MKK4-expressing SKOV3ip.1 microscopic metastases at 14 dpi (100× magnification). (**b**) More than 160 microscopic metastases were scored for size (in μm^2) and percent BrdU-positive cells using a computer aided image analysis system. Both size and BrdU incorporation were significantly decreased in HA-MKK4-expressing metastases compared to vector-only metastases ($P = 0.0003$ and $P < 0.0001$ respectively) (**c**) Immunolabeling for pH3 in vector-only and HA-MKK4-expressing SKOV3ip.1 microscopic metastases at 14 dpi (100× magnification). (**d**) More than 100 microscopic metastases were scored for size (in μm^2) and percent pH3-positive cells a both size and pH3 immunostaining for mitotic cells were significantly decreased in MKK4-expressing metastases compared to vector-only metastases ($P = 0.0008$ and $P = 0.004$ respectively). (Figure reproduced from data originally published by Lotan et al. [10])

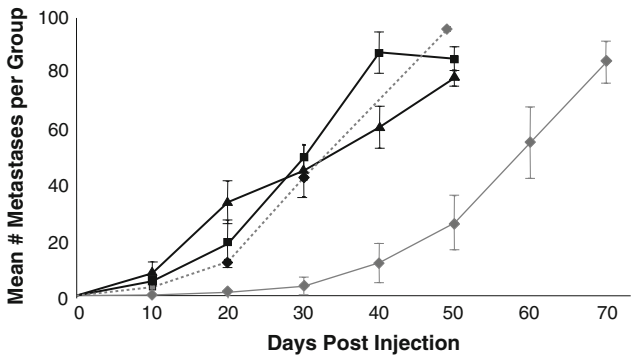

Fig. 3 Increased MKK4-expressing SKOV3ip.1 cell number can bypass metastasis suppression. 1×10^6 cells of three SKOV3ip.1-vector (black line, triangles), three SKOV3ip.1HA-MKK4-KR (black line, square), and four SKOV3ip.1-HA-MKK4 (gray line, diamonds) clonal cell lines were injected intraperitoneally into female SCID mice. Data from each group of clones were pooled, with the average number of metastases per group versus time displayed. Notably, when 1×10^7 SKOV3ip.1-HA-MKK4 (dashed gray line, diamonds) cells were injected, numbers of metastases formed were similar to the number produced by injection of 1×10^6 SKOV3ip.1-vector or SKOV3ip.1-HA-MKK4-KR cells

surge in studies of bacterial social interactions, primarily in the past decade, has shown that hundreds of diverse bacterial species are capable of cell-cell communication, via a chemical lexicon, and furthermore, that bacteria coordinate group behaviors and act in many respects like higher-multicellular organisms [16]. Quorum sensing involves the production, release, and detection of chemical signaling molecules called autoinducers. As a population of quorum-sensing bacteria grows, the concentration of released autoinducer increases proportionally with cell number. When the extracellular autoinducer concentration reaches a critical threshold level, the group detects the molecule and responds to it with a population-wide alteration in gene expression. Thus, linking alterations in gene expression to autoinducer levels enables bacteria to act like multicellular organisms. Quorum sensing controls processes including the production and secretion of virulence factors, sporulation, bioluminescence, and DNA exchange [17–19]. Quorum sensing also regulates the development of complex structures called biofilms.

A biofilm is a community of bacterial cells adhered to a surface or to each other which becomes encased in a self-produced polymeric matrix. Bacteria living in biofilms have increased resistance to antimicrobial agents and are better able to withstand environmental stress [20]. Studies have identified some of the environmental cues that signal the cells to initiate biofilm formation, the proteins that

mediate this response, and the physical processes involved in forming these complex structures. The biofilm formation process appears similar to metastatic colonization. A comprehensive review of the salient literature enabled us to compare these two seemingly disparate processes. A summary of our findings is presented in Fig. 4. Specifically, we present a comparison between steps in metastatic colonization (upper panel), bacterial biofilm formation (middle panel), and a summary of characteristics common to both processes (lower panel). It should be noted that in order to specifically address the biological data presented in Figs. 1–3, we have focused our discussion on metastatic colonization. Thus, the model summarized in Fig. 4 does not consider the potential contributions of a quorum sensing-like mechanism on tumor initiation and growth which are biologically and molecularly distinct processes [5].

In response to environmental signals such as cellular stress, bacteria can initiate biofilm formation. As in metastatic colonization, to complete this process cells must: (1) escape from the primary site and move to secondary sites; (2) adhere to and survive on target surfaces; (3) form microcolonies; and (4) develop into complex multicellular structures [20–23]. Both free-swimming bacteria and those dispersed from a mature biofilm can initiate this process. In the latter case, bacteria produce enzymes to degrade the polymeric matrix to facilitate escape. Surface attachment is determined by both turbulent flow and by physiochemical properties of the system. Motile bacteria can also use flagella to reach a target surface. Attachment is mediated by adhesins, secreted polysaccharides, and structures such as pili. Once cells have attached, they no longer require flagella, and instead utilize pili-mediated twitching motility which allows the bacteria to move along the surface and organize into monolayers [21, 22]. Multicellular behaviors are initiated by microcolonies**,** communities of bacterial cells that are three to five layers deep and are embedded in an extracellular polysaccharide substance (EPS) [23]. After surface attachment and microcolony formation, mature biofilm structures can form [20]. The end result of this quorum-sensing-process is the development of structures which are strikingly similar to metastases. This leads us to the notion that as with bacteria, overt metastasis formation could be mediated by a quorum-sensing-signaling circuit analogous to those previously identified [13, 16, 17, 24, 25].

Quorum sensing provides a unifying and testable model for many long-observed behaviors of metastatic cells

A variety of population-dependent behaviors, such as plasticity of gene expression and phenotype, formation of complex multicellular structures, the switch from a persistent to an active (pathogenic) phenotype, drug resistance, and response to cytokines have been described in metastatic models. In general, these behaviors have been viewed as resulting from the tendency of malignant cells towards heterogeneity. To our knowledge, the concept that these diverse behaviors are the product of a regulated cell signaling mechanism, such as quorum sensing, has not been rigorously tested. Of particular relevance is the observation that cell density at the time of preparation can have a dramatic, nonlinear effect on the number of metastases produced in an experimental metastasis assay (e.g. tail vein or intraperitoneal metastasis assays) [26, 27]. Historically assays are designed to yield a reproducible quantity of overt metastases in a defined period of time. As we considered the literature and standards of practice we formulated the following relationship between yield, number, density, and time. The yield (Y) of experimental metastases for a given model is a function of the number of cells injected (N), the density (d) of cells at the time of preparation for injection, and the time (number of days) of the assay (t). For clarity we will represent this nonlinear relationship as:

$$\boxed{Y \approx f(N, d, t).}$$

Depending on N, metastases can develop shortly after injection/implantation or following prolonged periods. A particular t is selected that gives a reproducible Y, maximizes animal welfare, and fits other experimental constraints. Thus, the Y produced at a given t is highly dependent upon both N and d. To our knowledge we are the first to formalize this relationship, however the biological phenomena have been long-recognized by metastasis researchers.

There are multiple lines of evidence suggesting a relationship between increased population number or cell density and increased metastatic ability in experimental metastases systems. For example, work by Hill et al. demonstrated that cells grown to a larger population size had increased metastasis formation compared to the same number of cells grown to a small population size [28]. The authors of this work found that metastatic variants were generated during the expansion of cells and the mechanism by which this occurred was likely epigenetic and transient. Along the same lines, the effect of cell density on metastatic behavior is illustrated by data from Welch et al. in which the relative number of metastases formed by rat mammary adenocarcinoma clones increased as cells d increased. These critically important but often overlooked data are reproduced in Fig. 5 [27]. Confluence was defined as the maximum number of cells per unit area without causing changes in cell cycle distribution.

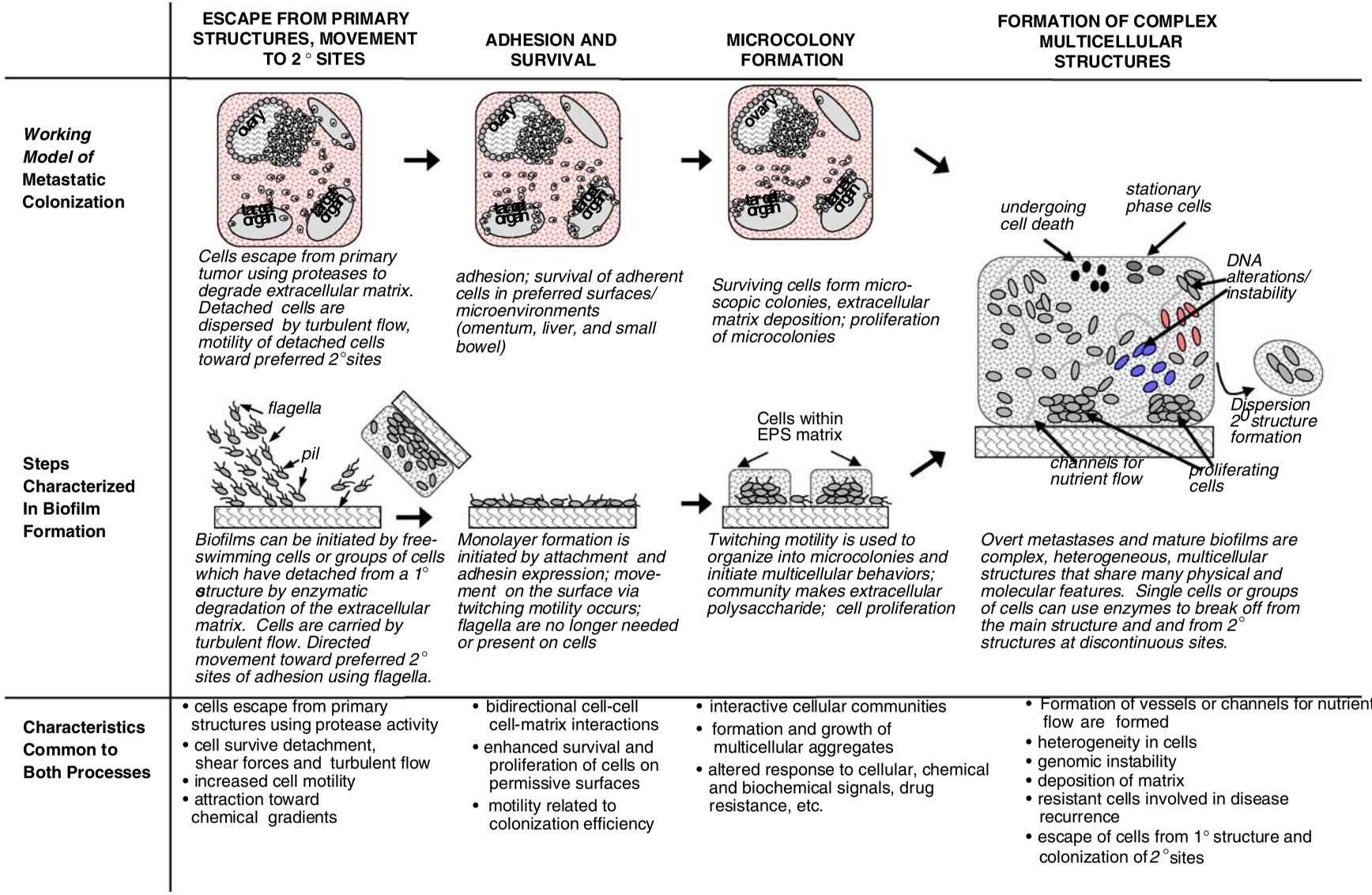

Fig. 4 Comparison of the processes of metastatic colonization and biofilm formation. The process of biofilm formation has many of the hallmarks of metastatic colonization including motility of cells toward appropriate surfaces (organ specific homing), attachment and interaction of cells with each other, surface adhesion and colonization (tumor cell-stromal cell interactions), remaining subclinical until sufficient cell population densities are reached to mount an effective attack on the host (dormancy), formation of complex, heterogeneous, structures containing channels for nutrient flow (formation of vascularized metastatic lesions), and development of subpopulations of therapy-refractory cells which can remain and can cause disease recurrence (persistors)

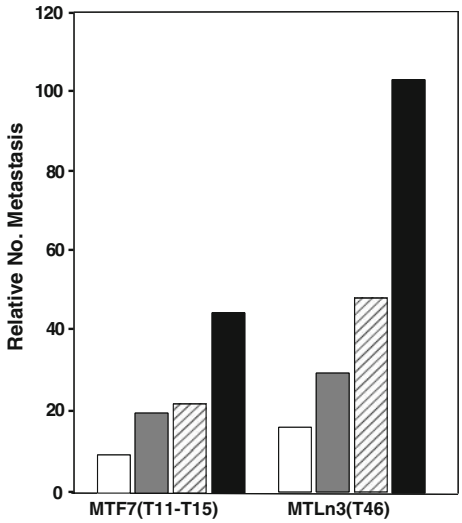

Fig. 5 Relative metastatic efficiency of rat mammary adenocarcinoma cell clones grown to different levels of confluence. Cells were grown to either 20% (white bars), 50% (grey bars), 70% (slashed bars), or 100% (black bars) prior to preparation for experimental (tail vein) metastasis assays. (This figure was adapted from data originally published by Welch et al. [27])

Simply changing *d* by 30% changed *Y* by 50%. These data strongly suggest that some properties required for metastasis are transient and depend on the interactions of groups of cells. Because subtle changes in *N* or *d* can have a large, nonlinear effect on *Y*, most assays/models likely use an excess of cells rather than a minimum *N* needed for a specific *Y* since most studies focus on the ability of an external factor, such as a drug treatment or expression of a gene, to modulate *Y*. In essence, most models of experimental metastasis use a large *N* grown at high-*d*, potentially skewing the cells toward maximal efficiency in putative quorum-sensing-dependent behaviors. In view of quorum-sensing principles, however, these conditions may not represent the environmental complexity in either spontaneous metastasis animal models or clinical disease.

There is further evidence that metastatic cells display quorum-sensing-dependent behavior. As previously stated, quorum sensing provides a cell-counting mechanism that allows bacteria to determine their population size and coordinate group activities. There are multiple lines of evidence supporting the notion that eukaryotic cells may use similar counting mechanisms. We postulate that although malignant cells have derangement of normal growth controls, they nonetheless retain innate counting mechanisms. In bacterial quorum-sensing systems, the concentration of an autoinducer increases proportionally with cell number and when the autoinducer reaches a critical threshold, the group responds with a synchronous change in behavior. Thus, autoinducer activity can be assayed by preparing conditioned medium from cells at high-density and transferring it to cells that are at low-density. Following addition of the high-density conditioned medium, the low-density cells are assayed for the premature activation of behaviors that are ordinarily only expressed by high-density cells.

The ability of the high-density conditioned medium to "trick" low-density cells into exhibiting high-density behaviors is the hallmark of a quorum-sensing mechanism. We were delighted to find that data published by Welch et al. in 1994 show that metastatic cells can exhibit quorum-sensing behavior [26]. These provocative data are reproduced in Fig. 6. In an effort to better understand the effect of *d* on *Y*, Welch et al. tested the possibility that high-density cells secreted a paracrine factor that increased the metastatic efficiency of cells. Representative data using MTLn3 cells are summarized in Fig. 6. Conditioned medium from 70% and 100% confluent plates increased the *Y* by $\sim$50%. Interestingly, conditioned medium from cells at 20% confluence suppressed *Y*. Our quorum-sensing hypothesis suggests that high-density MTLn3 cells secreted an "autoinducer" that caused low-density cells to produce

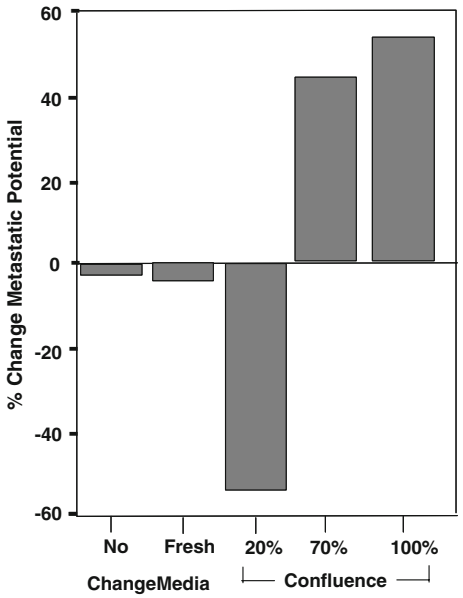

Fig. 6 Percentage change of experimental metastatic efficiency of low-density MTLn3 cells following exposure to conditioned medium collected from MTLn3 cells at various levels of confluence. Conditioned medium was collected following 48 hours of continuous culture from MTLn3 cells seeded to yield levels of 20%, 70%, or 100% confluence at the time of conditioned medium collection. All recipient cultures were seeded 48 h previously to yield 50% confluent cultures. Conditioned medium was added for 4 h prior to preparation for experimental metastasis assays. As controls, either the medium was not replaced, or it was replaced with fresh medium. The results were confirmed using serum-free medium. (This figure was adapted from data originally published by Welch et al. [26])

the *Y* of high-density cells. Further, one can use the conceptual and experimental framework of quorum sensing to design studies to identify both known and novel signals that modulate metastatic efficiency. We believe that re-examining salient findings in the metastasis literature from the viewpoint of quorum sensing enables a fresh and different perspective.

Translational potential

While specific proteins and cellular phenotypes have been associated with metastasis, there is no well-characterized in vivo empirical model that integrates these attributes into a coherent understanding of the unique aspects of ovarian cancer metastasis. Such a model would serve as a framework for the integration of clinical and experimental data and enable quantitative assessment of the temporal and spatial events in ovarian cancer metastasis. From a practical standpoint, a comprehensive model of ovarian cancer behavior which considers a quorum-sensing component may allow us to understand some of the tumor biology that is unique to this cancer type and that baffles clinicians. It is known that surgical cytoreduction of metastatic implants to less than 1 cm or to microscopic disease results in prolonged patient survival. This finding has heightened the debate concerning whether it is the biological properties of the individual patient's tumor that allows maximal cytoreduction or surgical effort. If the model presented here is correct, it could result in improved patient survival by explaining a shift in the tumor environment after surgery such that there are smaller populations of cells able to take advantage of quorum sensing. Such findings would highlight the need to decrease cell density in ovarian cancer populations, possibly by direct treatment with intraperitoneal chemotherapy to reduce cell-dense populations or by repetitive attempts at surgical cytoreduction.

In acknowledging the possibility that a quorum-sensing-like phenomenon exists in cancer cells, we may go forward by targeting new mechanisms used by cancer cell populations to improve patient survival. For instance, development of drug-resistant metastases is a common clinical problem. Data from the bacterial studies have shown that blocking quorum-sensing signaling molecules in drug resistant bacteria may restore susceptibility to antimicrobial therapy [20, 23, 29, 30]. If this phenomenon likewise exists in ovarian cancer cells, it provides an unexplored target for antimetastatic therapy. Further, if ovarian cancer populations utilize quorum-sensing signaling molecules, it may be feasible to target disruption of production or detection of these signals to enhance response to established forms of treatment such as chemotherapy.

Final thoughts

The prevailing dogma remains that metastasis is the result of the "drive" of malignant cells towards growth [31]. Mechanisms based on this view established a model where acquisition of metastatic ability is the product of mutation-selection cycles and derangement of cell growth, selecting for the most aggressive (malignant) clones. This parallels the view that long dominated the field of microbiology. Indeed, even today the concept of quorum sensing remains relatively or completely unknown to many outside the field of microbiology. With respect to cancer, the prevailing view is that cancer cells are "lone agents" and disease is caused by the most malignant cells. As pointed out by Heppner [32] "this view does not consider population biology and plasticity of cancers. Many lines of evidence suggest that the behavior of metastases, like other mixed populations, may not be governed simply by the behavior of its most deviant members. Instead tumors (*and metastases*) [1] may be cell societies, ecosystems in which the various members (clones) interact to produce a group dynamic that define overall behavior" [33]. Further, the mutation-selection paradigm does not account for the dynamic character of metastatic cells readily observed in a variety of cancer types [34–36]. We propose that it would be beneficial to revisit seminal data in the metastasis literature from the viewpoint of quorum sensing. In this view, selection may be for the population that is best able to coordinate its efforts in order to sense and respond to changing conditions and overtake its host, rather than a deterministic process that selects for the most aggressive malignant cells. It is anticipated that other models can be formulated that can provide a theoretical framework for testing the complex and dynamic behaviors of cell interacting in populations. However, it is our view that a model which addresses and incorporates these issues, and we suggest that a quorum-sensing model does, could provide insight into novel molecular mechanisms underlying the metastatic process and may provide novel therapeutic targets.

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c-Jun NH_2-Terminal Kinase Activating Kinase 1/Mitogen-Activated Protein Kinase Kinase 4–Mediated Inhibition of SKOV3ip.1 Ovarian Cancer Metastasis Involves Growth Arrest and p21 Up-regulation

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Abstract

In many patients without clinical metastases, cancer cells have already escaped from the primary tumor and entered a distant organ. A long-standing question in metastasis research is why some disseminated cancer cells fail to complete steps of metastatic colonization for extended periods of time. Our laboratory identified c-Jun NH_2-terminal kinase activating kinase 1/mitogen-activated protein kinase kinase 4 (JNKK1/MKK4) as a metastasis suppressor protein in a mouse xenograft model of experimental i.p. ovarian cancer metastasis. In this model, expression of JNKK1/MKK4 via activation of p38 delays formation of ≥1-mm implants and prolongs animal survival. Here, we elucidate the time course of this delay as well as the biological mechanisms underpinning it. Using the Gompertz function to model the net accumulation of experimental omental metastases, we show that MKK4-expressing implants arise, on average, 30 days later than controls. Quantitative real-time PCR shows that MKK4 expression does not have a substantial effect on the number of cancer cells initially adhering to the omentum, and terminal deoxyribonucleotidyl transferase–mediated dUTP nick end labeling analysis shows that there is no increase in apoptosis in these cells. Instead, immunohistochemical quantitation of cell cycle proteins reveals that MKK4-expressing cells fail to proliferate once they reach the omentum and up-regulate p21, a cell cycle inhibitor. Consistent with the time course data, *in vitro* kinase assays and *in vivo* passaging of cell lines derived from macroscopic metastases show that the eventual outgrowth of MKK4-expressing cells is not due to a discrete selection event. Rather, the population of MKK4-expressing cells eventually uniformly adapts to the consequences of up-regulated MKK4 signaling. [Cancer Res 2008;68(7):2166–75]

Introduction

This year, 560,000 Americans will die from cancer, most of them from metastatic disease (1). In the majority of patients without detectable metastases, viable tumor cells have already escaped from the primary tumor and entered one or more distant organ sites (2, 3). The high recurrence rate after definitive local therapies, such as cytoreduction for ovarian cancer, shows the urgent need to identify patients at risk for disease recurrence as well as the need for antimetastatic therapies to treat the disease. Clinical and experimental studies have identified the final step in this process, metastatic colonization of secondary sites, as a tractable therapeutic target (4). Mechanisms regulating this clinically important process are being elucidated by studies of metastasis suppressor proteins that can specifically inhibit metastatic colonization (5).

Our laboratory identified c-Jun NH_2-terminal kinase activating kinase 1/mitogen-activated protein kinase (MAPK) kinase 4 (JNKK1/MKK4; hereafter referred to as MKK4) as a metastasis suppressor protein for ovarian cancer using a well-characterized SKOV3ip.1 xenograft model of experimental i.p. metastasis (6). As a key member of the stress-activated protein kinase (SAPK) signaling cascade, MKK4 can itself phosphorylate both the JNK and p38 MAPKs, resulting in the activation of transcription factors including activator protein 1 and activating transcription factor 1 (7, 8). Using SKOV3ip.1 cells (9), a metastatic human ovarian cancer cell line that lacks significant endogenous MKK4, we showed that ectopic expression of hemagglutin (HA)-tagged MKK4 reduces overt experimental metastasis formation by 90% in a kinase-dependent manner and that MKK4 signals through p38, and not JNK, to suppress *in vivo* metastatic colonization (6, 10). As is the case with other metastasis suppressors, SKOV3ip.1 cells expressing HA-MKK4 have no detectable alterations in the rate of growth or apoptosis under a variety of *in vitro* growth conditions (6). Thus, the suppressive effect of MKK4 on metastatic growth is dependent on *in vivo* activation of the protein. Interestingly, animals injected with MKK4-expressing cells show a 70% improvement in survival as compared with controls, but these animals will eventually succumb to disease burden (6, 10).

These findings raise several important questions: What are the biological mechanisms responsible for MKK4-mediated suppression of metastatic colonization? Can MKK4-expressing cells become resistant to the effects of MKK4? Building on our previous work, which supports a mechanism by which MKK4 signals through p38 to suppress metastatic colonization and that its suppressor activity is kinase dependent, we set out to determine how MKK4 acts at the cellular level in the clinically relevant microenvironment of the omentum to inhibit outgrowth of disseminated cells. Experiments were designed to examine how MKK4-expressing cells ultimately bypass this suppression. Using complementary approaches, we show that MKK4 does not significantly decrease the number of cancer cells adhering to the omentum, nor does it increase the number of apoptotic cells. Instead, MKK4-expressing cells attached to the omentum fail to proliferate and show a concomitant up-regulation of the cell cycle

Note: T. Lotan and J. Hickson are co-first authors.

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inhibitory protein p21. We also show that, contrary to conventional wisdom, the eventual outgrowth of MKK4-expressing cells is not due to a discrete genetic selection event. Rather, our data support a model in which the population of MKK4-expressing cells adapts to the consequences of MKK4 activation and down-regulates p21 expression, eventually forming macroscopic experimental metastases. Discerning the mechanisms that regulate MKK4-mediated suppression of colonization has significant clinical implications for the design of drugs and therapies aimed at controlling disseminated tumor growth. Conversely, understanding how some MKK4-expressing cancer cells bypass suppression and form overt lesions is also critical if we wish to lengthen the interval of suppression. This work represents important progress toward both of these translational goals.

Materials and Methods

Cell lines and culture conditions. Previously characterized SKOV3ip.1-pLNCX2 (vector) and SKOV3ip.1-HA-MKK4 clonal cell lines were maintained in standard conditions (10). To establish metastasis-derived cell lines, individual overt (i.e., ≥1 mm) lesions were excised and placed in 200 μL of dissociation medium [DMEM containing 5% FCS, 1% penicillin (100 units/mL)/streptomycin (100 μg/mL) mixture, 0.25 μg/mL amphotericin (Mediatech), and 12,500 units/mL collagenase (Worthington Biochemical)]. Samples were incubated for ~16 h at 37°C with shaking (200 rpm) to form a homogeneous suspension of dissociated cells. Cells were collected by centrifugation and the pellet washed once with PBS. Cells were resuspended and plated in growth medium in a 10-cm tissue culture dish.

Immunoblotting, immunoprecipitation, and *in vitro* kinase assays. For immunoblotting, 30 μg of total protein were prepared, resolved, transferred, and immunoblotted as previously reported (10). The primary antibodies and dilutions used were as follows: HA.11 (Covance; 1:1,000), p38 (Cell Signaling Technologies; 1:1,000), and phospho-p38 (Cell Signaling Technologies; 1:1,000). Probed membranes were stripped with Restore Western Blot Stripping Buffer (Pierce), washed, and blocked overnight before reprobing. Actin was used as a loading control (Calbiochem; 1:10,000).

To assess MKK4 kinase activity, SKOV3ip.1 cells were cultured in complete growth medium containing 0.1% FCS for 24 h and stimulated with 1 μg/mL anisomycin (Sigma) or ethanol control for 20 min before cell lysis, followed by immunoprecipitation, *in vitro* kinase assays, and resolution by SDS-PAGE (10). As a loading control, membranes were immunoblotted for p38 substrate using the following dilutions: primary (1:20,000), secondary (1:40,000).

Experimental metastasis assays in immunodeficient mice. Female athymic nude mice or beige nude XID (NIH III) mice (Harlan Sprague-Dawley; 4–6 wk old) were used for *in vivo* studies. Cells were not grown beyond 80% confluence before preparation for mouse injection. Cells (1×10^6; 500 μL of a 2×10^6 cells/mL solution) were injected i.p. (6). For determination of *in vivo* growth kinetics, a total of 165 mice were injected with one of three SKOV3ip.1-vector clones (clones 1–3) or four SKOV3ip.1-HA-MKK4 clones (clones 1–4; ref. 10). Every 10 d postinjection (dpi), three to five mice per clone were euthanized and the number of ≥1-mm-diameter metastases assessed during necropsy. SEs at each time point represent the data from 12 to 15 mice. For all other studies, animals were injected with one SKOV3ip.1-vector (clone 3) or HA-MKK4 cell line (clone 2) and sacrificed at the experimental end points (3, 14, 30, or 60 dpi).

Quantitative real-time PCR. Primers and a probe specific to an intronic portion of the human β-globin gene were used to detect human cells in mouse omentum (Integrated DNA Technologies). The sequences were as follows: human β-globin F, 5′-GAGGGTTTGAAGTCCAACTCCTAA-3′; human β-globin R, 5′-CAGGGTGAGGTCTAAGTGATGACA-3′; dual labeled reporter probe, 5′-FAM-ACCTGTCCTTGGCTCTTCTGGCACTG-BHQ-1-3′. To normalize against mouse DNA, mouse-specific primers specific to an intronic portion of β-globin were also designed: mouse β-globin F, 5′-GGCTGCCTGCCTTTAATTCA-3′; mouse β-globin R, 5′-GGTTAGCTTGGATAACCTGCTTTTT-3′; dual labeled reporter probe, 5′-FAM-AGGGATTGTCCTGTCCTTCCACGCTT-BHQ-1-3′. All DNAs were prepared from cells and tissues with the PUREGENE DNA Purification Kit according to the manufacturer's protocol (Gentra Systems). DNA from each omentum (for the standard curve and all experimental samples) was purified into 200-μL Tris-EDTA and subsequently diluted 1:10 before adding 1 μL of DNA to the quantitative reverse transcription-PCR (RT-PCR) reaction. Quantitative RT-PCR reactions were prepared using the Brilliant Probe-Based QRT-PCR Reagents (Stratagene) in a total volume of 25 μL: 2.5 μL 10× core PCR buffer, 4 mmol/L $MgCl_2$, 800 μmol/L deoxynucleotide triphosphates, 500 nmol/L forward primer, 500 nmol/L reverse primer, 200 nmol/L probe, 30 nmol/L ROX reference dye, 1.25 units Surestart Taq polymerase, and ~150 ng DNA template. Reactions were run and data analyzed on the MX3000 QRTPCR system (Stratagene) with a 10-min incubation at 95°C, followed by a two-step reaction: 95°C × 15 s and 64°C × 60 s for 40 cycles. All reactions were done in triplicate, with appropriate negative controls (100% mouse DNA for human primers, 100% human DNA for mouse primers, and water).

Histologic analysis and immunohistochemical staining of experimental metastases. For analysis of microscopic lesions, the omentum was excised from euthanized mice, fixed overnight in 10% neutral buffered formalin, processed, and embedded in paraffin. Tissue sections (5 μm) were prepared and stained with H&E for histologic analysis. Terminal deoxyribonucleotidyl transferase–mediated dUTP nick end labeling (TUNEL) assay was done with the Apoptag Plus *In Situ* Detection Kit as directed by the manufacturer (Chemicon). For immunohistochemical staining, tissue sections were rehydrated in three 5-min xylene washes, two 5-min 100% ethanol washes, and two 5-min 95% ethanol washes. Antigen retrieval was done in the microwave in sodium citrate buffer (pH 6) for all antibodies except for pan-cytokeratin staining, for which enzymatic digestion was done with 1 mg/mL proteinase K in PBS at 37° for 5 min. Endogenous peroxidase activity was blocked with 3% hydrogen peroxide for 15 min. Tissue sections were blocked in 5% goat serum for 1 h at room temperature. For pan-cytokeratin immunostaining, tissue sections were incubated for 1 h at room temperature with a rabbit polyclonal antiserum (1:1,000; DAKO). For bromodeoxyuridine (BrdUrd) and p16 immunostaining, tissue sections were incubated for 1 h at room temperature with a sheep polyclonal antiserum (1:2,000; Research Diagnostics, Inc.) or a mouse monoclonal antiserum (1:200; BD Biosciences), respectively. For phospho-histone H3, p21, and MKK4 immunostaining, sections were incubated at 4° overnight with a rabbit polyclonal antiserum (1:300; Upstate), a mouse monoclonal antiserum (clone SX118; 1:50; BD Biosciences), or a mouse monoclonal anti-MKK4 antibody (1:15; Novocastra Laboratories), respectively. For p27kip1 immunostaining, sections were incubated for 30 min at room temperature with a mouse monoclonal antiserum (clone SX53G8, 1:25; DAKO). Immunolabeling reactions were developed with the EnVision Plus detection system (DAKO) followed by counterstaining with hematoxylin. Mouse colonic mucosa served as a positive internal control for BrdUrd and phospho-histone H3, and tonsil and pancreatic islet cells were used as positive internal controls for p21 and p27kip1 staining, respectively. Tissue from a human nevus was used as a positive control for p16 immunostaining. Negative controls were isotype control rabbit/mouse IgG.

Immunohistochemical data analysis. For BrdUrd and phospho-histone H3 immunostaining of the 14 dpi omenta and p21 and p27 immunostaining of the 30 dpi omenta, an automated, computer-assisted image analysis system was used to score percentage of nuclei with positive staining (Chromavision). Immunostained histologic sections of each omentum were digitally scanned into the system at ×10 magnification, and each microscopic metastasis (14 dpi) was manually identified and scored for size (μm^2) and percentage of positively stained cells. For the 30 dpi omenta, multiple 10× fields were randomly chosen and scored for percentage of positively stained cells. For p21 and p27 immunostaining of the 14 dpi omenta, higher background staining necessitated manual scoring of tumor cells in each microscopic metastasis.

Mathematical modeling of *in vivo* growth kinetics in the SKOV3ip.1 model. A least squares nonlinear regression, based on the Marquardt-Levenberg algorithm for the iterative estimation of coefficients, was used to fit the number of overt implants observed in mice injected with either

SKOV3ip.1-vector (60 mice) or SKOV3ip.1-HA-MKK4 (105 mice) cells to a three-parameter Gompertz curve of the form

$$N_i(t) = N_{\max,i} e^{-e^{-(t-t_{o,i})/b_i}}$$

.

Here, the index i is used to distinguish vector from HA-MKK4; N_i *(t)* is the total number of overt (≥1 mm diameter) metastases present in the animal at time t; $t_{o,i}$ is the offset/delay time parameter; b_i is the growth rate normalization parameter, indicating the steepness of the Gompertz curve; and $N_{\max,i}$ is the maximum total number of overt metastases an animal can support irrespective of time [the asymptote $N_i(t)$ approaches as $t \to \infty$]. Huber/White robust standard errors were used to account for the intra-clone correlation. This sigmoidal model has previously been applied to describe the growth kinetics of cancer cells *in vitro* and primary tumors *in vivo* (11, 12). It is more biologically feasible than a simple exponential model because the doubling time for metastasis number changes over time (initially increases and then decreases) and it does not assume that the number of metastases increases infinitely.

Statistical analyses. First, the numbers of SKOV3ip.1-vector and SKOV3ip.1-HA-MKK4 cells present on the omentum 3 dpi were compared using a nonparametric Wilcoxon rank-sum test. Second, to stabilize the variance and normalize the data, a log transformation was applied to the size of metastases and an arcsine-root transformation was applied to the proportion of positive immunohistochemical staining of implants (TUNEL, BrdUrd, phospho-histone H3, p21, and p27) before further analysis, although results are still presented in original scale. Size of implants and proportion of positive staining cells were compared between the vector and HA-MKK4 groups using mixed effect linear models, treating each animal as a random effect because observations within each animal may be correlated. If the random effect was found be nonsignificant based on likelihood ratio test, the mixed effect model was reduced to a two-sample t test. Third, two-way analysis of variance was used to compare number of implants 30 dpi between vector and HA-MKK4 in both athymic nude mice and NIH III mice following a square root transformation on the number of implants. Finally, following square root transformation, the number of implants 30 dpi from the metastasis-derived HA-MKK4 cells lines (clones), the parental HA-MKK4 cell line, and a vector control were compared using a mixed effect linear model in which each clone was treated as random effect (because mice within each experiment were correlated). The Tukey multiple comparison procedure was used to adjust for multiple pairwise testing.

Results

Modeling the growth delay of MKK4-expressing cells. Expression of HA-MKK4 in SKOV3ip.1 cells significantly reduces the number of overt implants following i.p. injection and extends animal survival (6, 10). Eventually, however, even mice injected with HA-MKK4–expressing cells develop macroscopic metastases and succumb to their disease burden. We posited that mathematical analysis of these population-dependent events could assist in the formulation of hypotheses about how MKK4 suppresses colonization and how cells eventually overcome its suppressive effects. To this end, an *in vivo* time course assay was conducted to determine the rate of accumulation of overt experimental metastases in the SKOV3ip.1 model, as well as the extent and duration of suppression by MKK4 (Fig. 1). Animals injected with SKOV3ip.1-vector only cells (Fig. 1, –○–) had ~20 to 30 metastatic implants at 20 dpi, and by ~40 dpi animals succumb to the disease with 80 to 100 overt peritoneal metastases. As previously observed, animals injected with SKOV3ip.1-HA-MKK4 cells (Fig. 1, - -◆- -) showed only ~1 to 2 implants at 20 dpi and did not have 80 to 100 metastases until ~70 dpi.

Using all 165 data points, the kinetics of overt implant formation by both vector-only and HA-MKK4–expressing cells was mathematically modeled with the 3-parameter Gompertz function. In the saturated model with separate parameters ($N_{\max,i}$, $t_{o,i}$, b_i) for MKK4 and vector groups, $N_{\max}$ was not statistically significantly different between MKK4 and vector groups, suggesting that the ultimate burden of experimental metastases each animal faces does not depend on MKK4 expression. The reduced Gompertz model with same $N_{\max}$ (= 245.72) and the other two parameters varied by vector ($t_{o,i}$ = 40.83, b_i = 22.33) and MKK4 ($t_{o,i}$ = 72.21, b_i = 28.39) fit the data well (Fig. 1; coefficient of determination R^2 = 0.883). There was only a marginally significant difference in the overall shapes of the growth curves between vector-only and HA-MKK4–expressing cells (P = 0.087, for b_i between the two groups). Rather than necessitating a separate equation, the HA-MKK4 growth curve was simply shifted in time, with formation of experimental metastases delayed by an average of 30 days (P = 0.003, for $t_{o,i}$ between the two groups). This suggested that suppression and outgrowth of HA-MKK4 cells are due to the uniform behavior of the population and not to the selection of a subset of cells, as would occur with increased apoptosis or differential adhesion of cells to target tissues. The *in vivo* growth curve also indicated that the rate-limiting step in the development of overt metastases in MKK4-mediated suppression occurs in the first 20 dpi, after which animals injected with MKK4-expressing cells begin to accumulate overt implants at a rate similar to control cells. Based on these findings, we formulated three hypotheses: First, similar numbers of SKOV3ip.1-vector and SKOV3ip.1-HA-MKK4 cells attach to the omentum and survive. Second, SKOV3ip.1-HA-MKK4 cells will have a decreased proliferation rate as compared with the vector controls. Finally, outgrowth of HA-MKK4–expressing cells is due to an adaptative response of the population of cells and not selection of cells that have deleted or inactivated the HA-MKK4 transgene.

MKK4 expression does not have a substantial effect on the number of SKOV3ip.1 cells adhering to the omentum. *In vivo* growth of SKOV3ip.1 cells recapitulates the metastatic pattern of

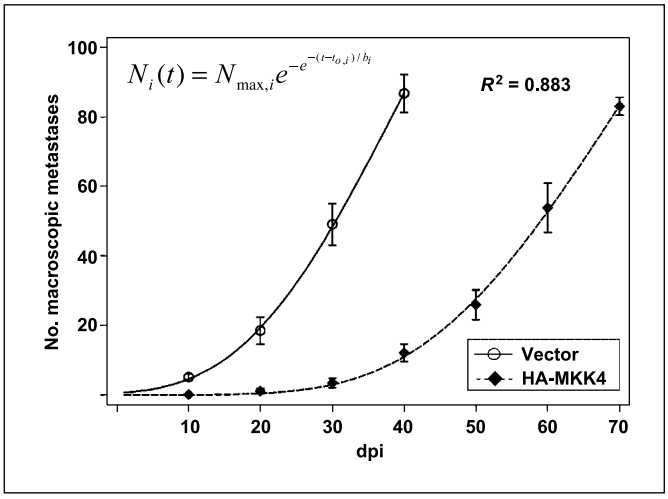

Figure 1. HA-MKK4–expressing cells are delayed in forming macroscopic metastases. The number of ≥1-mm metastases present as a function of time was determined by injecting SKOV3ip.1-vector (–○–) clones or SKOV3ip.1-HA-MKK4 (- -◆- -) clones i.p. into athymic nude mice and assessing the number of metastases every 10 d. *Points,* mean from 12 to 15 mice per time point; *bars,* SE. Nonlinear regression revealed that a three-parameter Gompertz model (*inset*) fit the 165 data points well (R^2 = 0.883), indicating that the shape of growth curve was similar between the two groups. HA-MKK4 cells showed an ~30-day delay in macroscopic metastasis formation compared with vector-only controls.

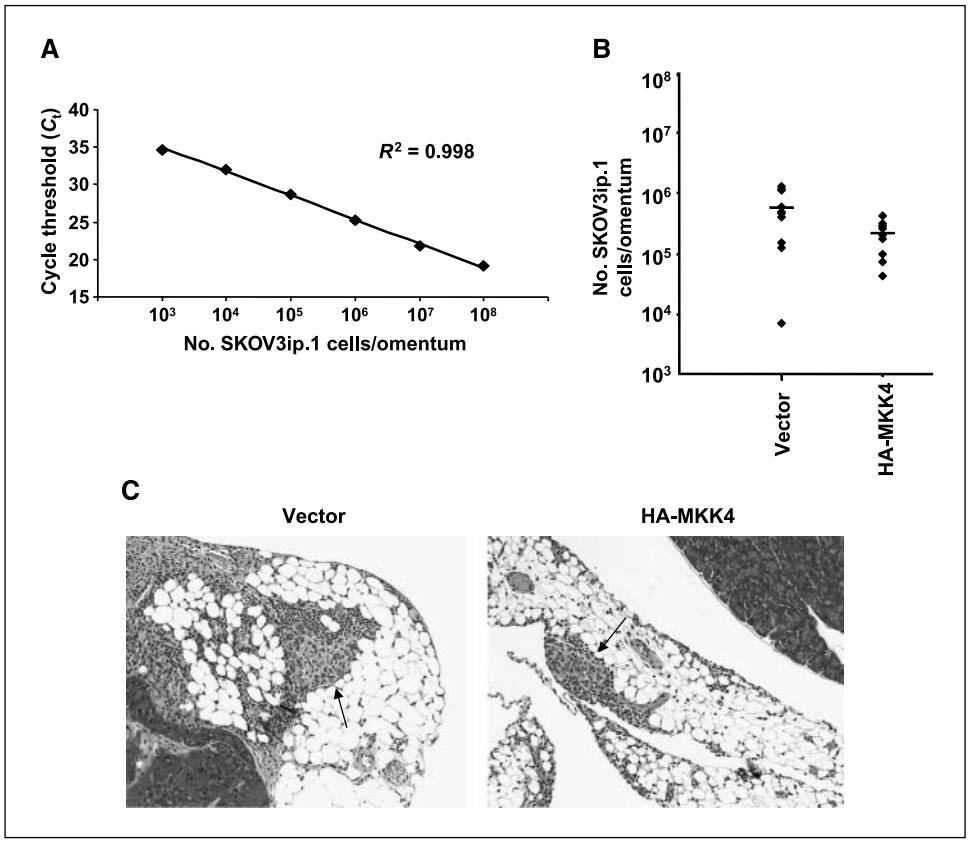

Figure 2. HA-MKK4–expressing and vector-only SKOV3ip.1 cells initially adhere to the omentum in similar numbers. *A,* a quantitative RT-PCR assay was designed to specifically amplify an intronic sequence in the human, but not mouse, β-globin gene. A standard curve was developed by mixing SKOV3ip.1 cell lysates with mouse omentum lysates, showing a range of detection between 1×10^3 and 1×10^8 SKOV3ip.1 cells. *B,* the number of SKOV3ip.1 cells present on the omenta from mice at 3 dpi was quantitated by quantitative RT-PCR assay. Data show that there are approximately twice as many vector-only cells adhering to the omenta as compared with HA-MKK4–expressing cells ($P = 0.06$). *C,* histologic sections of tumor implants show similarly sized tumor nodules in the two groups at 3 dpi (*arrows*; magnification, ×200).

human disease (6). In the experimental metastasis assay, MKK4 expression significantly delays the presentation of overt metastases; however, once HA-MKK4–expressing cells begin to form overt lesions, the temporal and spatial distribution of tumor burden is comparable to control cells (data not shown). To determine whether the delay in formation of SKOV3ip.1-HA-MKK4 experimental metastases is due to decreased adherence of injected cells, a quantitative real-time PCR assay was developed to quantitate the number of cells present on the omentum at 3 dpi. A standard curve was generated using genomic DNA from samples containing known numbers of SKOV3ip.1 (human) cells combined with mouse omentum homogenates, showing a range of detection spanning 10^3 to 10^8 SKOV3ip.1 cells in a background of mouse genomic DNA (Fig. 2*A*). At 3 dpi, there was not a significant difference between the numbers of vector-only and HA-MKK4–expressing cells present on the mouse omentum (vector mean, 5.8×10^5 cells; HA-MKK4 mean, 2.2×10^5 cells; $P = 0.06$; Fig. 2*B*). Further, the modest increase in the number of adherent vector-only cells at this time point was insufficient to account for the 10- to 20-fold decrease in macroscopic metastases formed by HA-MKK4–expressing cells at 20 dpi. Histologic sections of omental tumor implants at 3 dpi revealed discrete tumor nodules without any apparent size differences between the two groups, consistent with the RT-PCR data (Fig. 2*C*). Thus, MKK4-mediated suppression of metastatic colonization is not due to decreased adhesion of cells to the omentum.

Apoptosis is not increased in HA-MKK4–expressing microscopic metastases. To address the possibility that MKK4 induces apoptosis in SKOV3ip.1 cells once they have adhered to i.p. structures, histologic sections of early implants (14 dpi) were prepared and TUNEL reaction was done. At 14 dpi, vector-only implants are ~10 times larger than those composed of HA-MKK4–expressing cells on histologic cross section ($P < 0.0004$, Fig. 3*A*), confirming that the MKK4-mediated growth delay is already occurring. Quantification of TUNEL-positive cells in >25 vector-only or HA-MKK4–expressing microscopic foci (from seven to eight animals each) revealed only rare apoptotic cells (<1%) in both groups ($P = 0.43$; Fig. 3*B*). Histologic examination of HA-MKK4–expressing microscopic foci at this time point revealed an inflammatory infiltrate composed of lymphocytes, histiocytes, and plasma cells surrounding the tumor cells in the athymic nude mice, with tumor foci highlighted by pan-cytokeratin immunostaining (Fig. 3*A*). Although nude mice have significantly decreased numbers of functional T cells, they retain a complement of B cells as well as increased levels of natural killer (NK) cells and macrophages (13). To address the possibility that HA-MKK4–expressing cells may preferentially invoke host immune response, leading to impaired proliferation, experimental metastasis assays were also conducted in beige nude XID (NIH III) mice, which lack functional T cells, B cells, and NK cells (14). By 30 dpi, beige nude XID (NIH III) mice injected with HA-MKK4–expressing cells show suppression comparable to that in athymic controls ($P < 0.0001$, HA-MKK4 compared with vector-only control; Fig. 3*D*) despite the lack of significant inflammatory infiltrate surrounding the keratin-positive tumor cells (Fig. 3*C, arrows*). Taken together, these studies allowed us to exclude induction of apoptosis or host immune response as being involved in MKK4-mediated suppression.

HA-MKK4–expressing microscopic implants show decreased proliferation. To address the possibility that MKK4-expressing cells are deficient in proliferation, SKOV3ip.1 vector-only and

HA-MKK4 cells were injected into athymic nude mice, and at 14 dpi, animals were injected with BrdUrd, subsequently sacrificed, and microscopic lesions were assessed for BrdUrd incorporation (a marker of S-phase cells) and phospho-histone H3 expression (a marker of M-phase cells). Analysis of >160 microscopic lesions expressing either vector-only or HA-MKK4 revealed that BrdUrd incorporation was significantly decreased in HA-MKK4–expressing cells (Fig. 4*A* and *B*; average of 6% versus 19% positive cells, $P < 0.0001$). Similarly, phospho-histone H3 staining showed decreased numbers of mitotic HA-MKK4–expressing cells (Fig. 4*C* and *D*; average of 0.7% versus 2.5% positive cells, $P = 0.004$). Consistent with our hypotheses, MKK4-expressing cells show decreased proliferation.

HA-MKK4–expressing microscopic metastases have increased levels of p21. The decrease in both BrdUrd incorporation and phospho-histone H3–positive cells in HA-MKK4–expressing microscopic lesions suggested that fewer cells were traversing S phase and subsequently M phase compared with controls. This finding, coupled with the fact that these cells eventually proliferate to form macroscopic implants, is consistent with a reversible cell cycle arrest. This prompted us to study the expression of cell cycle inhibitory proteins potentially acting in the HA-MKK4–expressing microscopic lesions. SKOV3 cells are known to be null for a variety of cell cycle inhibitors including p53 and p16 (15–17); thus, protein expression of p21(Waf1/Cip1) and p27(Kip1) was quantified in HA-MKK4–expressing microscopic metastases at 14 dpi. p16 immunostaining provided a negative control for this series of experiments (Fig. 5*A*). This approach revealed that p21 expression was increased nearly 10-fold in HA-MKK4–expressing microscopic lesions compared with vector-only controls (average of 9% versus 1%, $P < 0.0001$; Fig. 5*B*). Nuclear p27 was only modestly increased in HA-MKK4–expressing cells and was of marginal statistical significance (average of 5% versus 1%, $P = 0.03$; Fig. 5*C*). Given that only a proportion of the total population of SKOV3ip.1 cells are in cell cycle at any given time point (with 19% entering S phase in a 4-hour window), the observed increase in p21 immunostaining (9% of the population) is biologically relevant and, combined with decreased BrdUrd incorporation and phospho-histone H3 staining, is consistent with our hypothesis that MKK4-mediated suppression of colonization is due to impaired cellular proliferation.

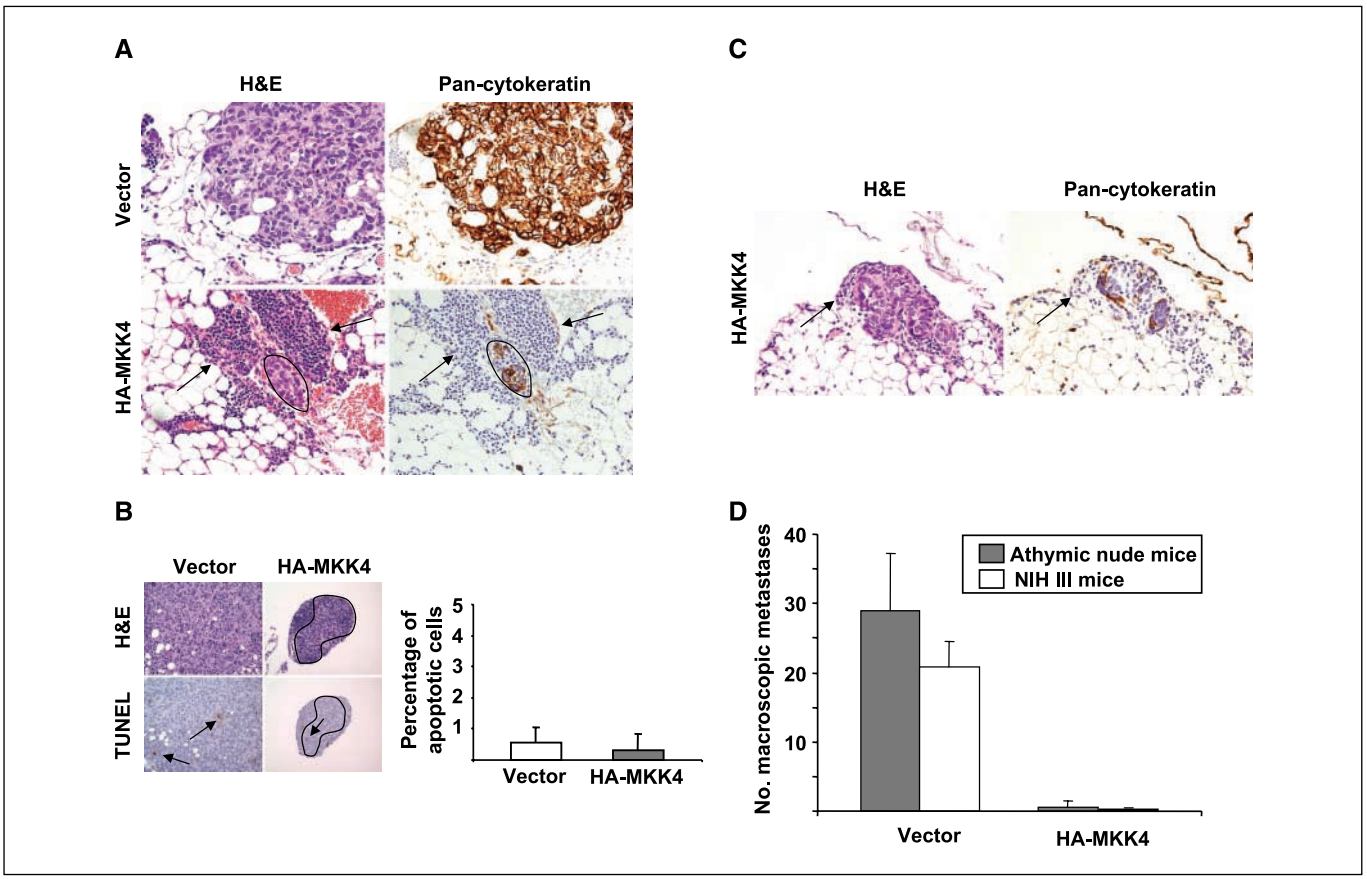

Figure 3. The *in vivo* growth delay of HA-MKK4–expressing cells cannot be attributed to increased apoptosis or surrounding host immune infiltrate. *A,* a quantitative histologic assessment of tissues scanned at ×100 magnification showed that by 14 dpi, vector-only metastases are ~10-fold larger than HA-MKK4–expressing metastases ($P < 0.0004$). HA-MKK4–expressing microscopic metastases (*bottom*, delineated by black circles; ×400 magnification) are surrounded by an inflammatory infiltrate composed of lymphocytes, histiocytes, and plasma cells in the athymic nude mice (*arrows*), and tumor cells are highlighted by pan-cytokeratin staining (*right*). *B,* TUNEL reaction for apoptotic cells shows only rare positive cells (*left, arrows*) in both groups (magnification, ×200). Quantification of TUNEL-positive cells (*right*) in >25 vector-only or HA-MKK4–expressing metastases arising in seven to eight animals each revealed <1% apoptotic cells in both groups ($P = 0.43$). *C,* at 14 dpi, beige nude XID (NIH III) mice injected with HA-MKK4–expressing cells showed microscopic metastases comparable in size and histology to those in athymic nude mice but with only a scant inflammatory infiltrate (*left, arrow*; ×400 magnification). Tumor cells are highlighted by pan-cytokeratin immunostaining (*right*). *D,* by 30 dpi, HA-MKK4–expressing cells were similarly suppressed for macroscopic metastasis formation in NIH III mice compared with athymic controls ($P < 0.0001$, for HA-MKK4 in both groups of mice compared with vector-only controls; $n = 5$ for each bar in graph).

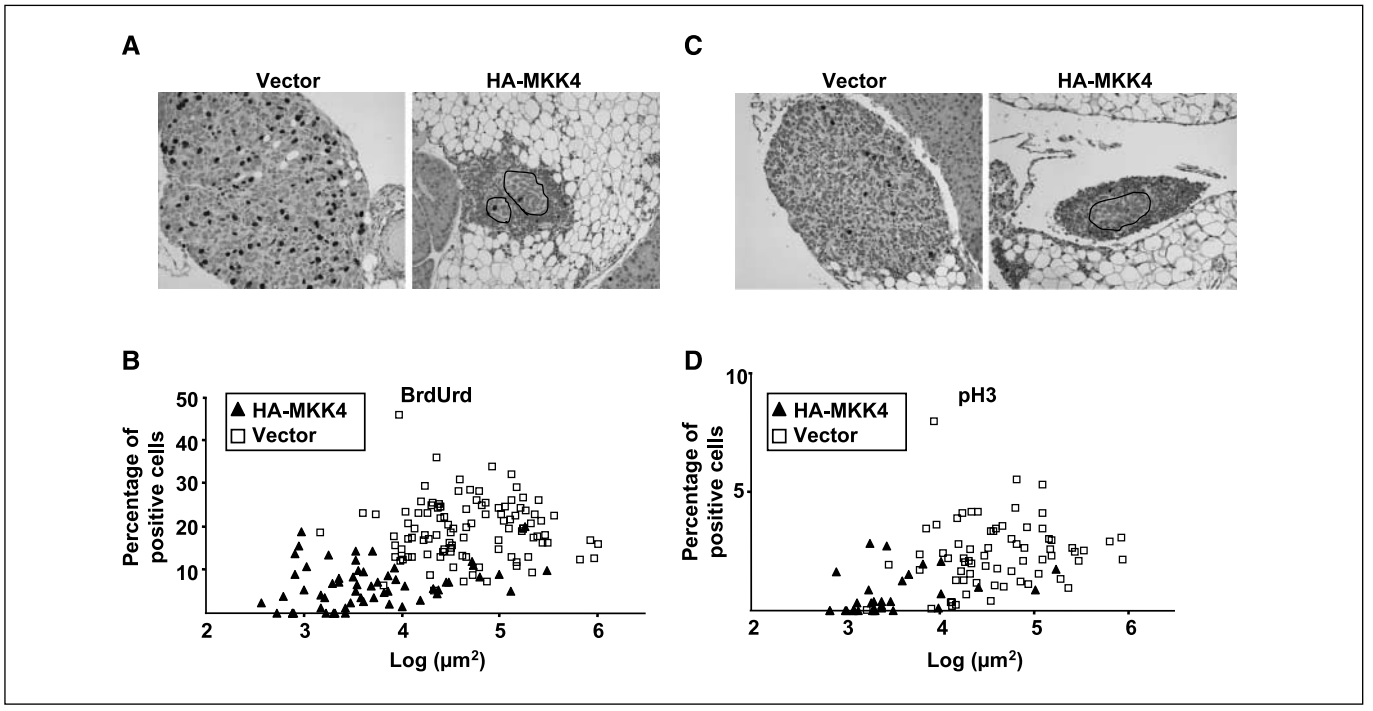

Figure 4. HA-MKK4–expressing microscopic metastases show decreased proliferation as assessed by BrdUrd incorporation and phospho-histone H3 staining at 14 dpi. *A,* BrdUrd was injected i.p. 4 h before the experimental end point. Immunolabeling for BrdUrd in vector-only and HA-MKK4–expressing SKOV3ip.1 microscopic metastases at 14 dpi (×100 magnification). *B,* more than 160 microscopic metastases were scored for size (in square micrometers) and percent BrdUrd-positive cells using a computer-aided image analysis system. Both size and BrdUrd incorporation were significantly decreased in HA-MKK4–expressing metastases compared with vector-only metastases ($P = 0.0003$ and $P < 0.0001$, respectively). *C,* immunolabeling for phospho-histone H3 in vector-only and HA-MKK4–expressing SKOV3ip.1 microscopic metastases at 14 dpi (×100 magnification). *D,* more than 100 microscopic metastases were scored for size (in μm^2) and percent phospho-histone H3 (*pH3*)–positive cells using a computer-aided image analysis system. Both size and phospho-histone H3 immunostaining for mitotic cells were significantly decreased in MKK4-expressing metastases compared with vector-only metastases ($P = 0.0008$ and $P = 0.004$, respectively).

Metastasis-derived SKOV3ip.1-HA-MKK4 cell lines retain expression of functional MKK4 protein and remain suppressed for metastatic colonization when repassaged through naïve mice. Our data that both vector only– and HA-MKK4–expressing populations of experimental metastases undergo uniform expansion suggested that the eventual outgrowth of HA-MKK4–expressing cells is the result of a population-wide adaptation to the consequences of SAPK signaling. This model prompted the hypothesis that the outgrowth of HA-MKK4–expressing cells was not due to selection of cells having deleted or functionally inactivated HA-MKK4. To test this, overt implants arising from HA-MKK4–expressing SKOV3ip.1 cells at ~65 dpi were evaluated by immunostaining (Fig. 6*A*). The data show that these overt experimental metastases do, in fact, continue to express HA-MKK4, indicating that no selection occurred (Fig. 6*A*). To expand on these findings, 25 independent metastasis-derived cell lines were established from mice injected with HA-MKK4–expressing SKOV3ip.1 cells. Continued expression of HA-MKK4 in these metastasis-derived cell lines was confirmed by immunoblotting for the HA-epitope tag (representative data are shown in Fig. 6*B*). By kinase assay, all of the SKOV3ip.1-HA-MKK4 metastasis-derived cell lines retained biochemically functional HA-MKK4 and phosphorylated p38 (representative data shown in Fig. 6*B*).

Although metastasis-derived SKOV3ip.1-HA-MKK4 cell lines retain expression of HA-MKK4, which can be artificially activated *in vitro*, it is possible that these cells have undergone other permanent molecular changes that will inactivate the MKK4 signaling module of the SAPK signaling pathway. If selection is indeed occurring, reinjection of these cell lines in our standard experimental metastasis assay should result in increased experimental metastasis formation compared with the parental HA-MKK4–expressing SKOV3ip.1 clones. To this end, metastasis-derived SKOV3ip.1-HA-MKK4 cell lines were assayed *in vivo*. Compared with vector-only cells, MKK4 metastasis-derived lines were still suppressed in their ability to form overt experimental metastases (mean of 29.6 ± 8.1 versus 4.8 ± 5.5, $P < 0.0001$) when reinjected into naïve mice (Fig. 6*C*). Taken together, these *in vitro* and *in vivo* data strongly suggest that the eventual outgrowth of HA-MKK4–expressing cells is not due to selection for clones of cells that have permanently altered their MKK4 signaling status, but is rather due to adaptation of the population to the biological consequences of SAPK signaling. Consistent with this idea, p21 protein expression is down-regulated in the overt HA-MKK4–expressing implants (30 dpi; Fig. 6*D*) compared with the earlier levels of expression in the microscopic metastases (14 dpi; Fig. 5*A*). In fact, by 30 dpi, there was no difference in p21 expression between HA-MKK4 and vector-only cells ($P = 0.49$; Fig. 6*D*). Collectively, these studies support the hypothesis prompted by the kinetic analysis that outgrowth of HA-MKK4–expressing cells is due to a population-wide adaptation of the cells to microenvironmental stimuli.

Discussion

Understanding the function of metastasis suppressor proteins can potentially help to identify patients at risk for progressive

metastasis development as well as identify antimetastatic therapies. Our laboratory and others identified MKK4 as a metastasis suppressor protein in clinical and experimental ovarian cancers. Immunolabeling of human tissues showed that MKK4 protein expression is significantly down-regulated in ovarian cancer metastatic implants compared with normal ovarian epithelium (6). *In vitro*, MKK4 expression does not affect inherent proliferation or increase cell death of SKOV3ip.1 cells (6). Rather, cumulative findings show that MKK4 exerts its effect in a context-dependent manner *in vivo* (10).

Since our initial report of the metastasis suppressor activity of MKK4, other laboratories have also examined its presence and expression in a variety of malignancies. For example, a recent study using digital karyotyping of clinical ovarian carcinoma specimens identified the MKK4 locus as a deleted "common" target of small interstitial deletions on human chromosome 17, and down-regulation of MKK4 is frequently observed in ovarian serous carcinoma tissues (18). Moreover, differential expression array analysis identified high MKK4 expression as a predictor of improved response to surgical debulking of ovarian cancers (19). Despite the considerable clinical and biochemical evidence for a role for MKK4 in inhibiting the spread of ovarian cancer, a number of important questions remained unanswered at the inception of the current work.

What are the biochemical and biological mechanisms by which activated MKK4 suppresses metastasis formation? An inherent property of signaling molecules is that their activation is dependent on the strength and duration of specific environmental stimuli. Consistent with this fundamental attribute of signaling kinases, JNKK1/MKK4 protein is only activated and functional when an appropriate external signal is received. In the case of suppression of experimental metastasis formation, this signal is provided to SKOV3ip.1-HA-MKK4 cells by interaction with the *in vivo* microenvironment. Building on our previous findings that MKK4 signals through the p38 MAPK to suppress experimental metastasis formation, we set out to determine how MKK4 acts at the cellular level to inhibit this process. A kinetic analysis of metastatic growth allowed us to formulate testable hypotheses about the rate-limiting steps involved in suppression of metastatic colonization. Complementary studies found that MKK4-mediated growth arrest of cancer cells was associated with up-regulation of p21 expression. Surprisingly, despite the fact that p38 has a well-established role in apoptosis (20, 21), we failed to detect any effect of MKK4 expression on the incidence of cell death in disseminated tumor cells on the omentum. Similarly, decreased adhesion of cells to the omentum does not play a significant role in suppression.

How might p21 up-regulation play a role in suppression of SKOV3ip.1 metastatic colonization? The association between MKK4-mediated suppression of colonization and up-regulation of p21 in the present study is intriguing. The p21 cell cycle inhibitor was originally identified as a p53 target gene (22), a protein that interacted with cyclin-dependent kinase (CDK; ref. 23), and a protein that is markedly up-regulated in cellular senescence (24, 25). Like many tumor cell lines, SKOV3ip.1 cells lack functional p53, and thus up-regulation of p21 in this system is necessarily p53 independent (16). Previous work has shown that p21 can be induced by p53-independent mechanisms (26), including induction by the p53-related molecule p73 (27). However, at least one recent study has suggested that SKOV3 cells do not express p73 (28). This finding needs to be addressed in our model system. In the absence of p53 and p73, p21 levels could be affected by posttranslational mechanisms that regulate p21 protein stability. Interestingly, recent

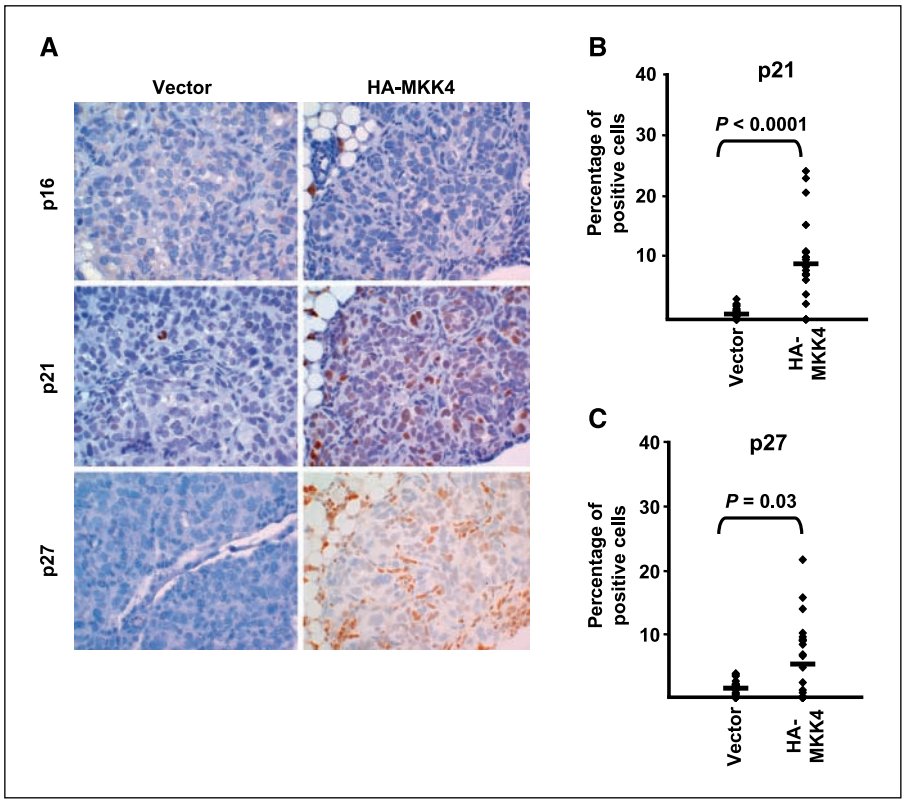

Figure 5. HA-MKK4–expressing microscopic metastases show increased p21 expression at 14 dpi. *A,* immunohistochemical staining for p16, p21, and p27 expression in day 14 metastases (×200 magnification). *B,* p21 nuclear expression was scored in >20 individual microscopic metastases from eight mice injected with either vector-only or HA-MKK4–expressing SKOV3ip.1 cells at 14 dpi. The mean percent of positive cells in SKOV3ip.1 cells vector-only and HA-MKK4 was 1% and 9%, respectively ($P < 0.0001$). *C,* p27 nuclear expression was scored in >20 individual microscopic metastases from three to five mice with either vector-only or HA-MKK4–expressing microscopic metastases at 14 dpi. The mean percent of positive cells in vector-only versus HA-MKK4–expressing cells was 1% and 5%, respectively ($P = 0.03$).

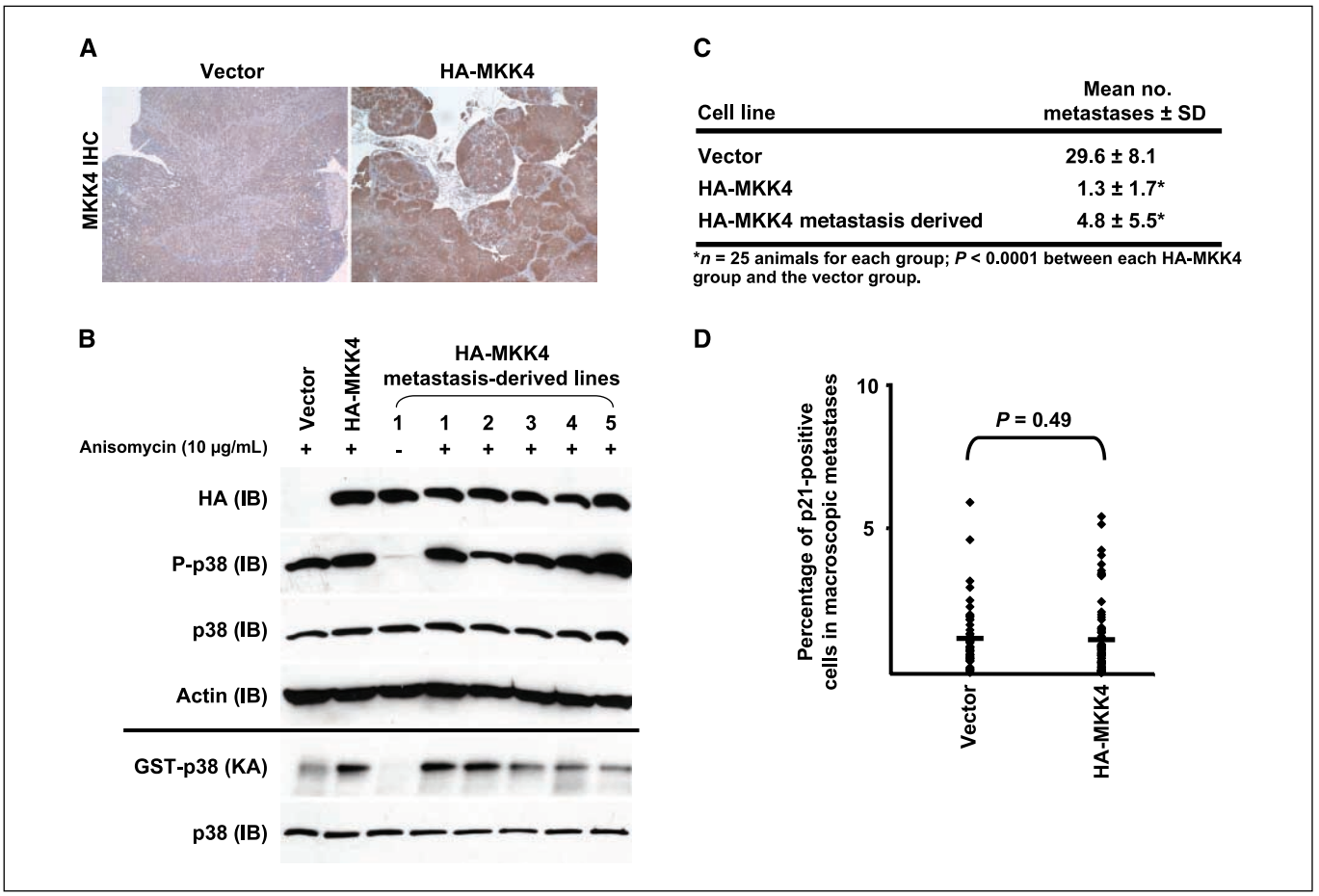

Figure 6. Cell lines derived from macroscopic metastases developing in animals injected with HA-MKK4–expressing SKOV3ip.1 cells retain expression of functional MKK4 *in vitro* and remain suppressed for metastasis when reinjected into naïve mice. *A,* immunohistochemical staining for MKK4 in macroscopic metastases derived from vector-only and HA-MKK4–expressing cells at 30 and 65 dpi, respectively (×40 magnification). SKOV3ip.1 cells have low endogenous MKK4 levels, as seen here in vector-only cells. MKK4 was consistently detected in macroscopic HA-MKK4 metastases. *B,* clonal cell lines were derived from >25 independent SKOV3ip.1-HA-MKK4 macroscopic metastases and screened for the presence of HA-tag, endogenous phospho-p38, p38, and actin after stimulation with anisomycin (representative data are shown). In addition, *in vitro* kinase assays (*KA*) were done to confirm that the HA-MKK4 protein is functional. Kinase assays show that HA-MKK4 is functional *in vitro* and phosphorylates glutathione *S*-transferase (GST)-p38 substrate in a manner similar to parental cell line controls (positive control; *second lane*). As a loading control, the blot was also probed for the GST-p38 substrate (*bottom*). *IB,* immunoblot. *C,* all five metastasis-derived cell lines in *B* were reinjected into five mice each for the standard end-point metastasis assay. These cell lines were equally suppressed for macroscopic metastasis formation at 30 dpi compared with parental lines ($P < 0.0001$, for both groups compared with vector control). *D,* quantitation of p21 immunolabeling in macroscopic metastases (30 dpi) from vector- and HA-MKK4–expressing cells. Sixty to eighty separate 10× fields in macroscopic metastases were scored for p21 immunolabeling on an automated image analysis system from six to seven animals in each group. p21 expression is comparable in both groups by the time macroscopic metastases have developed ($P = 0.49$) and is down-regulated in HA-MKK4–expressing cells by 30 dpi compared with the same cells at 14 dpi (Fig. 5).

in vitro studies have established a biochemical link between SAPK activation and p21 protein levels (29–31). Kim et al. (30) showed that p38-α induced phosphorylation of p21 at Ser^{130} *in vivo* and promoted p21 stabilization, thereby showing a connection between p38 activation and p21 up-regulation.

Taken together, these studies support the notion that p21 may play an important role in MKK4-mediated suppression of metastatic colonization. However, additional studies will be required to elucidate the precise mechanism of this effect. Notably, p21 has a known role in both reversible cell cycle arrest and irreversible cellular senescence. p21 promotes cell cycle arrest *in vivo* through inhibition of CDK activity and activation of pRb in response to numerous signals including DNA damage (32), cytokine signaling (33), and cellular aging (34). The fact that the cell cycle arrest associated with MKK4 expression in our system is apparently reversible, with eventual outgrowth of MKK4-expressing metastases, suggests that the observed growth arrest is not due to cellular senescence. Given that SKOV3ip.1 cells retain functional pRb (17), which is essential for senescence, our work suggests that we may be able to restore the capacity for permanent growth arrest by preventing the eventual down-regulation of p21. In fact, there are currently agents under study *in vitro* and in early clinical trials that specifically target p21 (35, 36).

As the molecular mechanisms of other metastasis suppressor proteins are increasingly well characterized, there is evidence that p21 overexpression and subsequent cellular growth arrest/senescence may mediate suppression in multiple systems. Recently, the metastasis suppressor protein CD82, also known as KAI1, was reported to enable disseminated cancer cells to attach to the vascular endothelial cell surface through interaction with the Duffy antigen receptor for chemokine protein (37–39). This interaction inhibits tumor cell proliferation through induction of senescence with associated up-regulation of p21. Together with the data presented for MKK4, this potentially represents a conserved

biological mechanism underlying the function of multiple metastasis suppressor proteins.

How do MKK4-expressing cells escape suppression and what approaches might be implemented to augment its antimetastatic effects? An important but infrequently discussed consideration in the development of antimetastatic therapies based on metastasis suppressor protein function is how cells may ultimately escape or bypass suppression. A long-standing paradigm of metastasis biology is that the process of both spontaneous and experimental metastasis selects for clones that have undergone permanent molecular changes (such as DNA mutation or deletion) enabling them to complete all steps of the metastatic cascade. Studies were conducted to address the possibility that outgrowth of MKK4-expressing metastases was due to such a canonical selective process. Data presented here show that this is not the case. Careful evaluation of the accumulation of overt experimental metastases over time in our model system showed that MKK4 expression does not significantly affect the overall shape of the metastatic growth curve. Further, MKK4 protein expression is retained in overt metastases and their derived cell lines; the MKK4 protein is functional in standard biochemical assays; and MKK4-expressing metastasis-derived cell lines remain suppressed when reinjected into naïve mice. These results suggest that the population of MKK4-expressing cells homogeneously adapts to the consequences of SAPK signaling and eventually down-regulates p21, enabling outgrowth of metastases.

These novel findings have strong relevance with respect to the dynamic and reciprocal interactions between cancer cells, stromal cells, and other microenvironmental components. In our model system, SKOV3ip.1 cells expressing MKK4 may become resistant to an external stimulus by secretion of a paracrine factor or perhaps by modulating their microenvironment through mechanisms such as stromal reprogramming. We are currently developing complementary *in vivo* and *in vitro* approaches to identify the specific cellular (e.g., host cell-cancer cell interactions), molecular (e.g., matrix components), and physical factors (e.g., cancer cell number and or density), which contribute to activation of MKK4 in SKOV3ip.1 cells during early time points in the process of metastatic colonizaton. Discerning the global and specific processes involved will yield important information about the temporal and spatial activation of MKK4 metastasis suppressor function. MKK4 and other metastasis suppressor proteins with well-characterized biochemical functions may provide new molecular tools for the dissection of the population-dependent interactions of the cancer cells with their microenvironment. Ultimately, it is our goal to use this information to extend the duration of suppression of metastatic colonization. Such findings could have significant implications for the control of clinical ovarian cancers.

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