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Human tumors instigate granulin-expressing hematopoietic cells that promote malignancy by activating stromal fibroblasts in mice

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Systemic instigation is a process by which endocrine signals sent from certain tumors (instigators) stimulate BM cells (BMCs), which are mobilized into the circulation and subsequently foster the growth of otherwise indolent carcinoma cells (responders) residing at distant anatomical sites. The identity of the BMCs and their specific contribution or contributions to responder tumor growth have been elusive. Here, we have demonstrated that Sca1+cKit– hematopoietic BMCs of mouse hosts bearing instigating tumors promote the growth of responding tumors that form with a myofibroblast-rich, desmoplastic stroma. Such stroma is almost always observed in malignant human adenocarcinomas and is an indicator of poor prognosis. We then identified granulin (GRN) as the most upregulated gene in instigating Sca1+cKit– BMCs relative to counterpart control cells. The GRN+ BMCs that were recruited to the responding tumors induced resident tissue fibroblasts to express genes that promoted malignant tumor progression; indeed, treatment with recombinant GRN alone was sufficient to promote desmoplastic responding tumor growth. Further, analysis of tumor tissues from a cohort of breast cancer patients revealed that high GRN expression correlated with the most aggressive triple-negative, basal-like tumor subtype and reduced patient survival. Our data suggest that GRN and the unique hematopoietic BMCs that produce it might serve as novel therapeutic targets.

Introduction

Patients diagnosed with 1 malignant neoplasm are at a greatly increased risk of presenting with multiple, independent primary cancers within a relatively short time period after the initial diagnosis (1, 2). As an example, some breast cancer patients develop contralateral breast cancer, which is a predictor of poor outcome (3, 4), and patients with synchronous bilateral breast cancer tend to have a significantly worse overall survival than those patients with metachronous or unilateral cancers (5). In addition to secondary tumors, patients with recurrent disease often present with multiple metastases that appear to arise suddenly and synchronously. As was recently reported, surgical resection of primary breast cancers significantly improved the survival time of patients who presented with distant metastases at the time of their primary diagnosis (6, 7). While there are a number of possible explanations for these diverse clinical observations, experimental evidence demonstrates that certain tumors can affect the behavior of other tumor(s) residing at distant anatomical sites (reviewed in ref. 8). The mechanisms underlying these systemic interactions between multiple dispersed tumors within a host are poorly understood.

In our own work, we reported that certain tumors can foster the growth of other tumors or disseminated metastatic cells located at distant anatomical sites in host animals (9). These studies revealed that certain tumor cells that would otherwise remain indolent are capable of responding to systemic cues to become overt tumors (9). Thus, when we implanted vigorously growing human breast carcinomas (which we termed instigators) in host mice, they stimulated both the outgrowth of otherwise poorly tumorigenic, indolent transformed cells (which we termed responders) residing at contralateral sites as well as the colonization of otherwise weakly metastatic cells residing in the lungs. We termed this endocrine stimulation systemic instigation. Importantly, instigated responding tumors were formed exclusively from the implanted responder cells and were therefore not seeded by metastatic cells originating in the instigating tumor (9).

A number of reports have demonstrated that tumors employ various means to actively perturb host organs at distant anatomical sites and that these perturbations are a driving force in tumor progression (reviewed in ref. 8). In our own experiments, we showed that instigating tumors perturb the BM of the tumor-bearing host by activating BM cells (BMCs) via a process that depended on secretion of osteopontin (OPN) by instigating tumor cells. Thus, when we mixed the indolent responder cells directly with BMCs from instigating tumor-bearing hosts prior to implantation, the admixed BMCs were able to instigate the growth of the otherwise indolent responder cells; admixed BMCs from control mice that did not bear an instigating tumor failed to do so (9).
Under situations of systemic instigation, such activated BMCs apparently became mobilized into the circulation, after which they were recruited into the stroma of the distant, otherwise indolent responding tumors. These observations, as well as those of others, have demonstrated that certain types of BMCs are functionally activated even prior to their mobilization into the circulation and subsequent recruitment to both primary tumors and distant indolent metastases (9, 10).

These clinical and experimental observations highlighted the need for a better understanding of the systemic mechanisms that operate to induce growth of tumors that would otherwise remain indolent. Thus, our previous studies did not reveal the identity of the activated BMC subpopulation or subpopulations that represent the key intermediaries between the instigating and responding tumors. Furthermore, other than promoting their growth, the precise benefits that the instigator-activated BMCs confer on responding tumors have been elusive. Accordingly, we undertook studies to deepen our understanding of the endocrine instigation process and to identify the mechanisms by which BMCs that are activated by instigating tumors are able to facilitate the outgrowth of responding tumors.

**Results**

**Histopathology of responding tumors that arise as a consequence of systemic instigation.** To begin to elucidate the mechanisms by which responding tumor growth is instigated, we chose to examine the histopathology of instigated responding tumors. To do so, we injected either BPLER (11) or MDA-MB-231 human breast cancer cells as instigators subcutaneously into one flank of Nude mice and weakly tumor-igenic, transformed mammary epithelial HMLER-HR cells (12) as responders into the contralateral flanks of these mice (Figure 1A). In control groups of mice, we injected either noninstigating tumor cells (PC3) or Matrigel vehicle contralaterally to the indolent responder cells (Figure 1A). Consistent with our previously reported results, the responding cells formed rapidly growing tumors only in the presence of the contralateral instigating tumors (Figure 1B and Supplemental Figure 1A; supplemental material available online with this article; doi:10.1172/JCI43757DS1) without any evidence of being seeded by disseminated instigator cells (9).

Striking differences were observed when we compared the histopathology of the responding tumors that had grown opposite instigating tumors with the few, small control responding masses...
that eventually appeared. In particular, we examined these various tumors for the presence of αSMA-positive myofibroblasts and collagen deposition, both of which are hallmarks of a reactive, desmoplastic stroma (13).

Responding cell masses recovered from sites contralateral to Matrigel plugs displayed very little collagen deposition or αSMA expression (Figure 1C). In fact, the few αSMA-positive cells that we did observe within these growths also expressed the pericyte marker NG2 and were associated with expression of the mouse endothelial cell antigen MECA32 (data not shown). These findings indicated that the αSMA-positive cells present in these masses were capillary-associated pericytes rather than myofibroblasts (14, 15).

In striking contrast, αSMA-positive cells and collagen were distributed widely and uniformly throughout the responding tumors that had been implanted contralaterally to either BPLER or MDA-MB-231 instigating tumors (Figure 1C and Supplemental Figure 1B). Staining for αSMA in these responding tumors overlapped only to a minimal extent with the staining for NG2 and MECA32 (Supplemental Figure 1C and data not shown), indicating that the majority of αSMA+ cells in these instigated tumors were myofibroblasts rather than capillary-associated pericytes. Such myofibroblast-rich, reactive stroma is almost always observed in malignant human adenocarcinomas and is associated with invasiveness and poor prognosis (16, 17). We also noted features of stromal desmoplasia, though not as well developed, in the lung metastases that formed in the presence of subcutaneously implanted instigating tumors (Supplemental Figure 2).

CellProfiler image analysis (18, 19) revealed that the area covered by αSMA-positive cells was 3-fold higher in the instigated tumors than that in the control tumors (P = 0.001; Figure 1E). In fact, these levels of αSMA staining approached those observed in the contralateral instigating tumors (Figure 1, C and E). We could not include analysis of responding tumors residing opposite noninstigators, as no responding tumors formed under these circumstances. We also calculated the average number of responding tumor cells, as determined by positive staining for the large T antigen (LgT) (Figure 1D and Supplemental Figure 1B). We determined that the numbers of responding tumor cells within these masses were significantly higher in the instigated tumor masses than in controls (P = 0.006; Figure 1F).

Hence, the increase in tumor mass that we observed as a consequence of systemic instigation was due to expansion of both the epithelial and stromal compartments within the instigated tumor tissues. Moreover, recruitment of myofibroblasts into responding tumors was initiated on a systemic level, regardless of the sites where responding tumors resided.

Influence of activated BM cells on responding tumor histopathology.

One previously noted consequence of systemic instigation is the enhanced recruitment of BM-derived cells into the responding tumor stroma (9). Moreover, BMCs extracted from instigator-bearing mice, when mixed directly with responding tumor cells, could
stimulate the growth of responding tumors and thereby mimic the effects of systemic instigation (9). This response provided us with a functional test of the biological status of the BM, specifically, of the ability of its component cells to expedite indolent tumor growth. We exploited this test to determine whether the stromal desmoplasia observed in the responding tumors implanted opposite instigating tumors was phenocopied by the admixed BMCs prepared from instigator-bearing animals.
Thus, we mixed responding tumor cells with BMCs prepared from mice bearing either Matrigel plugs or BPLER instigating tumors prior to implantation (Figure 2A). In consonance with our previous work, admixture of BMCs from instigator-bearing animals increased the incidence of tumor formation from approximately 40% to 85% and enhanced the size of those tumors that did form by a factor of approximately 3 relative to tumors to which control BMCs had been admixed (Figure 2B).

We found that the admixed BMCs, like contralaterally implanted instigating tumors, influenced the histopathology of the responding tumors. Thus, when control BMCs from Matrigel-bearing mice were mixed with the responder cells, the resulting growths were devoid of desmoplastic stroma (Figure 2C). In these small masses, αSMA+ cells were restricted to blood vessels, indicating that they were capillary-associated pericytes (data not shown). In marked contrast, αSMA+ cells and collagen were abundant and distributed uniformly throughout the stroma of responding tumors resulting from the mixture of the responder cells with BMCs from instigator-bearing mice (Figure 2C and not shown); in these tumors, αSMA stained not only pericytes but also the myofibroblasts (Supplemental Figure 3). Hence, the reactive tumor stroma resulting from admixture of BMCs from instigator-bearing mice closely phenocopied the stroma of responding tumors implanted opposite instigating tumors.

BMCs do not differentiate into responding tumor myofibroblasts. Fibroblasts and myofibroblasts are known to confer a variety of physiologic benefits on tumors (20, 21). Thus, our observations suggested that the mechanism by which responding tumor growth was instigated depended on their ability to recruit myofibroblast-rich tumor-supportive stroma.

These initial observations did not reveal the mechanistic connection(s) between tumor growth and the formation of a reactive stroma, nor did they reveal whether the activated BMCs present in instigator-bearing mice contain progenitors of the stromal myofibroblasts. Reported observations vary on this point; some reports indicate that tumor myofibroblasts have origins in the BM and/or circulation, while others suggest that the nearby normal tissue of the host serves as the immediate source of tumor myofibroblasts (22–24). To resolve between these alternatives, we examined the responding tumors that arose as a result of systemic instigation in host mice that had previously received BM transplants from donor mice expressing GFP (Rag1−/− eGFP‡tg mice; ref. 9) (Figure 2D). While GFP+ BM-derived cells were indeed incorporated into the stroma of instigated responding tumors that had formed in the recipient
mice, GFP+ myofibroblasts were extremely rare in these tumors (Figure 2E); we also found this to be true of the stroma of instigating tumors. Thus, when we counted GFP+ αSMA+ cells under the confocal microscope, we observed that none of the stromal myofibroblasts were derived from the BM in the 2 different instigating tumor types that we examined (not shown). These observations indicated that the BMCs present in instigated tumor stroma did not serve as direct precursors of stroma-associated myofibroblasts. Instead, these recruited BMCs played another role in stromal development, such as facilitating the recruitment and/or transdifferentiation of myofibroblasts from nearby tissues.

Identification of instigating BM cells. For these reasons, we attempted to identify the specific subtype or subtypes of BMCs that were responsible for the effects of systemic instigation. We previously
reported that Sca1+cKit– BMCs were the most abundant BM-derived cell type incorporated into the responding tumors that had been stimulated by instigating tumors. Moreover, Sca1+cKit– BMCs were incorporated in significantly greater numbers into the stroma of responding tumors implanted contralaterally to instigating tumors than those that were implanted opposite control or noninstigating tumors (9). At the same time, we reported that Lin–Sca1+cKit+ BMCs were reduced in numbers in the marrow of mice bearing instigating tumors as compared with control hosts.

To further characterize these various BMC subpopulations, we harvested cells from the marrow of mice bearing instigating tumors and fractionated them by FACS into Sca1+cKit–, Sca1+cKit+, and Sca1-depleted fractions (Figure 3A). We then mixed each of these distinct BMC subpopulations separately with responding tumor cells and implanted the cell mixtures into mice to determine whether any of these subpopulations could participate in the formation of tumor stroma and accelerate responding tumor growth. Importantly, we mixed these various BMC subtypes in numbers that reflected their relative representation in the whole unfractionated BM.

When we mixed either 7.5 × 10^3 Sca1+cKit+ (Figure 3A) or 7.25 × 10^5 Sca1-depleted cells (Figure 3A) with 2.5 × 10^5 responder cells prior to injection into host mice, we found that neither population was capable of enhancing responding tumor growth to any significant extent above that of responder cells implanted on their own (Figure 3B). In fact, the few tumor masses that we recovered from such cell mixtures exhibited nondesmoplastic stroma with areas of necrosis and edema (Figure 3C).
In striking contrast, as few as $2.5 \times 10^4$ admixed Sca1+cKit− BMCs from instigator-bearing mice (Figure 3A) enhanced the growth of responding tumors, yielding tumors that were approximately 6-fold larger than masses formed from responding tumor cells implanted on their own (Figure 3B). The responding tumors that grew as a result of admixture of these Sca1+cKit− BMCs acquired a desmoplastic stroma in which αSMA+ myofibroblasts and collagen were uniformly and widely distributed (Figure 3C).

We therefore concluded that the tumor-promoting activity of the BM from instigator-bearing mice was attributable to the presence of an instigating Sca1+cKit− subpopulation of BMCs. Lin Sca1+cKit− cells have been described previously as a population of hematopoietic progenitor cells of unknown function (25, 26). Some reports suggest that various subsets of Sca1+cKit− cells can give rise to both lymphoid- and myeloid-biased precursors (27–29). We wished to determine whether the tumor-promoting activity of these Sca1+cKit− BMCs was unique to instigator-bearing mice, or whether, alternatively, the comparable population from control mice might exhibit this activity. First, we discovered that the representation of the Sca1+cKit− subpopulation was similar in the BM of tumor-bearing and control mice and that these cells represented less than approximately 2% of the total BM cellularity in all cases (Figure 3D). Accordingly, we sorted the Sca1+cKit− population from control Matrigel or noninstigator-bearing mice (Figure 3A) and mixed $2.5 \times 10^4$ of these cells with responder cells prior to implantation in host mice. Unlike the Sca1+cKit− BMCs from instigator-bearing mice, which had potent tumor-promoting ability, the same number of Sca1+cKit− BMCs from the marrow of mice bearing size-matched noninstigating tumors lacked this ability (Figure 3B). Thus, the control Sca1+cKit− BMCs did not enhance responding-tumor incidence or size.

### Table 1

#### Summary of enriched gene sets in granulin-treated fibroblasts

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<th>Gene ID</th>
<th>Fold change</th>
<th>q</th>
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<td>IL8</td>
<td>Interleukin 8</td>
<td>3576</td>
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**Gene symbol** | **Gene name** | **Gene ID** | **Fold change** | **q**  
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<td>Interleukin 10 receptor, beta</td>
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**GRN induces inflammation and matrix remodeling gene expression signatures in human mammary fibroblasts. Summary of gene sets enriched in human mammary fibroblasts treated with human rGRN (1 μg/ml) every 24 hours for 6 days as compared with control PBS treatment. Samples analyzed in triplicate. pZC denotes the P value computed using the Zhang C statistic; q denotes P value corrected for multiple testing.**

In striking contrast, as few as $2.5 \times 10^4$ admixed Sca1+cKit− BMCs from instigator-bearing mice (Figure 3A) enhanced the growth of responding tumors, yielding tumors that were approximately 6-fold larger than masses formed from responding tumor cells implanted on their own (Figure 3B). The responding tumors that grew as a result of admixture of these Sca1+cKit− BMCs acquired a desmoplastic stroma in which αSMA+ myofibroblasts and collagen were uniformly and widely distributed (Figure 3C).
of an instigating tumor, but that a subpopulation of cells in this compartment was functionally changed under conditions of systemic instigation. Therefore, we undertook to determine whether use of other cell-surface markers would allow us to identify the instigating BMC subtype with even greater precision. When comparing BMCs from instigator-bearing hosts to those of control Matrigel- or noninstigator-bearing hosts, flow cytometric analyses revealed no significant differences in the representation of Sca1+cKit– BMCs that bore additional, commonly studied cell-surface markers (Figure 3E). In the marrow from all groups of mice, approximately 95% of the Sca1+cKit– BMCs were CD45 positive, indicating that the majority of these cells were of hematopoietic origin (Figure 3E). In addition, there were no significant differences in the composition of the Sca1+cKit– BMCs among groups of mice when we examined cell-surface expression of the CD11b (~4%), CD11c (~9%), VEGFR1 (~2%), Gr1 (~3%), CD11b’CD45– (~4%), CD11b’Gr1– (~2%), and NK1.1 (~1%) markers (Figure 3E).

Taken together, these results revealed that (a) the Sca1+cKit– CD45+ subpopulation of BMCs from hosts bearing instigating tumors is highly enriched for the functional activity that promotes responding tumor growth; (b) BMCs exhibiting the Sca1+cKit–CD45+ profile, although equally represented in number in the BM of all groups of mice, differed in their biological activity when prepared from the BM of instigator-bearing hosts relative to the BM of control hosts; and (c) analysis of commonly studied cell-surface antigens did not allow us to further resolve the subpopulation of BMCs within the Sca1+cKit– population that was responsible for systemic instigation.

Unique expression profile of instigating Sca1+cKit– BMCs. Since Sca1+cKit– BMCs from instigator-bearing and control mice were similar in their cell-surface antigen profiles, we sought other means to uncover possible changes in this subpopulation of cells that occur in response to systemic instigation. More specifically, we speculated that differences in gene expression might provide clues about their differing instigating abilities. Accordingly, we obtained gene expression profiles of FACS-sorted Sca1+cKit– BMCs from mice bearing instigating tumors and size-matched noninstigating tumors in order to identify genes that might be associated specifically with the instigating activity.

Analysis of the expression array data identified genes that were expressed at significantly different levels in the instigating Sca1+cKit– BMCs compared with their noninstigating counterparts (GEO GSE25620). The most differentially expressed gene (t = 5.3) was granulin (GRN, also termed granulin-epithelin precursor, proepithelin, acrogainin, or PC cell-derived growth factor) (Figure 3F). GRN belongs to the epithelin family of secreted growth factors and is expressed by numerous cell types, including hematopoietic cells, epithelial cells, and certain neurons (30). GRN has been shown to mediate inflammation, developmental cavitation, and wound healing and is highly expressed in surgical samples from patients with aggressive cancers (30). We validated these results in a larger number of samples by quantitative PCR and determined that GRN mRNA was significantly upregulated, approximately 2.5-fold, in instigating Sca1+cKit– BMCs relative to the counterpart BMCs prepared from Matrigel-bearing control mice, which lack instigating ability (Figure 2G).

Our analyses indicate that instigating tumors, even in the absence of metastasis to the BM, activate specific gene expression programs in a subset of hematopoietic BMCs, while noninstigating tumors fail to do so. Because GRN was the most differentially expressed of these genes, we wished to determine whether GRN-expressing BMCs are recruited into the responding tumors and, if so, what role GRN might play in responding tumor instigation.

GRN-expressing BMCs in responding tumor stroma and GRN in host plasma. We first asked whether host-derived GRN was evident in the tumors resulting from the admixture of responder cells with the instigating Sca1+cKit– BMCs – the class of cells in which we had identified upregulated GRN expression in the BM. Indeed, when Sca1+cKit– cells from the BM of instigator-bearing mice were mixed with the responder cells, the resulting tumors were highly positive for GRN (Figure 4A). The GRN+ cells in these tumors were also positive for Sca1 (Figure 4C), indicating that the admixed BMCs provided the source of host-derived GRN that we observed in these tumors.

In contrast, when Sca1+cKit– cells from the BM of Matrigel-implanted control mice were admixed, the resulting tumors displayed little, if any, GRN staining (Figure 4A). In fact, the extent of GRN positivity was approximately 5-fold higher in the tumors resulting from admixture of instigating BMCs as compared with the control BMCs (P < 0.01; Figure 4A). In this experiment, we could not include analysis of tumors resulting from admixture of BMCs from noninstigator-bearing mice, as such BMCs did not yield any responding tumors. Nonetheless, it was apparent that GRN positivity in responding tumors correlated well with the instigating ability of the BMCs that had been mixed with responding cells prior to implantation.

We wondered whether GRN-positive host BMCs were also recruited into the responding tumors that grew as a result of systemic instigation by contralaterally implanted instigating tumors. Responder cell masses that were implanted contralaterally to control Matrigel plugs displayed very little GRN positivity (Figure 4B). In marked contrast, the total stromal area marked by positive GRN staining was approximately 5-fold greater in the responding tumors that had grown opposite BPLER instigating tumors than was present in those implanted opposite Matrigel control plugs (P < 0.01; Figure 4B). Separate experiments conducted in mouse hosts that

### Table 2

Correlations between GRN expression and clinicopathologic features of patient breast tumors

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<th>Correlation coefficient</th>
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<td>Grade</td>
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<td>Ki67 3g</td>
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Data shown are for analysis of GRN staining on TMAs using antibody HPA028747. *No significant correlation. **Statistically significant positive correlations. ***Negative correlation.
had been transplanted previously with GFP+ BMCs confirmed that GFP/GRN double-positive cells were indeed incorporated into the stroma of responding tumors that had grown opposite the instigating tumors (Supplemental Figure 4A), indicating that recruited BMCs provided a source of host GRN in these tumors.

We also examined the responding tumors early in the instigation process, 4 weeks after responding tumor implantation. We found that the Sca1-positive cells recruited into these instigated tumors also expressed GRN (Figure 4C). This prompted us to examine the small tissue plugs that we recovered opposite noninstigated tumors 4 weeks after implantation. We found that there were no GRN-positive cells in these noninstigated plugs, as compared to their mobilization into the general circulation and that many GRN-expressing BMCs do not give rise to stromal myofibroblasts and confirmed our earlier observation that the great majority of the myofibroblasts in the stroma of instigating and responding tumors do not originate in the BM.

Effect of GRN on responding tumor growth. Our results, as described above, indicated that instigating tumors stimulate GRN expression within the Sca1+cKit+ fraction of hematopoietic BMCs prior to their mobilization into the general circulation and that many GRN-positive cells are subsequently found in the stroma of indolent tumors. We speculated that GRN secretion by these BM-derived cells might play a causal role in some aspect of systemic instigation, specifically in the development of the stromal desmoplasia in the instigated tumors. Accordingly, we tested whether soluble, recombinant pro-GRN (rGRN) protein would affect responding tumor growth and mimic systemic instigation. To do so, we subcutaneously implanted indolent tumor cells in Matrigel impregnated with various doses of rGRN (250 ng/ml and 2500 ng/ml, collectively referred to as high-dose rGRN; 2.5 ng/ml and 25 ng/ml, collectively referred to as low-dose rGRN). Moreover, throughout the experimental time course, we periodically administered injections of rGRN directly into the subcutaneous sites where responding tumor cells had previously been implanted.

Within 14 days, 50% of the responding cell implants treated with high-dose rGRN had formed externally palpable tumors, while only 17% of the low-dose rGRN and none of the PBS-treated cells did so (Figure 5A). By 77 days, 100% of the high-dose rGRN-treated responder cells had formed tumors, while only 50% of the low-dose rGRN and PBS-treated sites formed palpable masses (Figure 5A). At the experimental end point, the average final mass of the high-dose rGRN-treated tumors was significantly higher (2.7-fold) than that of the low-dose rGRN and PBS-treated tumors (P < 0.05; Figure 5B). We note here that comparable increases in the overall tumor mass have been observed by us repeatedly in the context of systemic instigation (9).

rGRN treatment also had a profound effect on the histopathology of the responding tumors. The cell plugs recovered from sites injected with either low doses of rGRN contained viable responder cells; however, these tumor cells appeared to form benign masses that did not resemble carcinomas (Figure 5C). These responding tumors did not contain αSMA+ cells and displayed little if any collagen deposition in their stroma (Figure 5D). Staining these tissues with anti-MECA32 antibody revealed that blood vessels were present within these masses (Figure 5D).

In striking contrast, the responder cells recovered from sites injected with high doses of rGRN formed tumors with a histopathology consistent with adenocarcinomas (Figure 5C). These
MECA32+ cells, suggesting that the majority of these cells were Sca1+cKit–CD45+ hematopoietic cells in the host BM. This suggested that the formation of the myofibroblasts might well arise through the GRN-induced transdifferentiation of existing fibroblasts residing in the tumor stroma or in adjacent normal tissue. Accordingly, we set up a series of cell culture experiments to examine the effects of human rGRN on human mammary stromal fibroblasts.

We cultured 2 different preparations of normal human mammary fibroblasts (hMF-1 and hMF-2) in the presence of various doses of human rGRN. Both populations of these fibroblasts had been isolated from patients undergoing reduction mammoplasty. We found that GRN enhanced expression of αSMA by human mammary fibroblasts in a dose-dependent manner (Figure 6, A and B). Both hMF-1 and hMF-2 treated with high-dose rGRN (1 μg/ml) exhibited significant increases in αSMA expression that were 23.9-fold (P = 0.008) and 6.2-fold (P = 0.009) higher, respectively, than that of PBS control–treated cultures (Figure 6B and Supplemental Figure 5A). In fact, in both cases, these levels of αSMA expression were significantly higher than that observed with 5 ng/ml recombinant TGF-β treatment (P = 0.01 each), which has been reported to induce αSMA expression in cancer-associated fibroblasts (CAFs) (31, 32) but had only a minor effect in our experiments. Consistent with our observations of the αSMA+ myofibroblast–rich responding tumors, we also confirmed that murine GRN significantly upregulated expression of αSMA in a dose-dependent fashion in mouse fibroblasts in vitro (Supplemental Figure 5B). Both normal fibroblasts and CAFs are heterogeneous, and different types of CAFs are thought to make distinct functional contributions to tumor growth (33–37). Moreover, markers that are shared in common by all fibroblasts have not been defined. Therefore, to investigate how GRN impinges upon fibroblast function beyond induction of αSMA expression, we treated triplicate samples of hMF-2 human mammary fibroblasts with either human rGRN (1 μg/ml) or PBS control every 24 hours for 6 days, prepared mRNA, and performed gene expression microarray analysis (Affymetrix U133 Plus).

We computed differentially expressed genes between rGRN-treated fibroblasts and PBS-treated fibroblasts and identified 138 differentially expressed probe sets (false discovery rate < 1%). Among the top genes induced in response to rGRN treatment, we observed several inflammatory cytokines and chemokines, including CXCL2, IL6, IL1B, CXCL1, IL8, CCL2, IL1A, CXCL3, CCL14, CXCL6 (Table 1; GEO GSE25619). Many of these genes have been recently included in a proinflammatory gene expression signature that was generated from the analysis of CAFs in mouse models of skin, mammary, and pancreatic cancers as well as in the cognate human cancers (37).

Enrichment testing against gene set collections provided by the Gene Ontology Consortium and Applied Biosystems revealed that gene sets related to cytokine- and chemokine-related immunity were enriched in the genes that were upregulated by GRN treatment (pZC < 0.0001; Table 1). In addition to these proinflammatory gene sets, the GRN–induced expression signature was enriched for genes that mediate integrin signaling (including laminins and various collagens) in our primary human mammary fibroblasts (pZC < 0.0004; Table 1).

**Effect of GRN on human mammary fibroblasts.** Our data support the notion that secretion of GRN by tumor-associated Sca1+cKit–hematopoietic BM-derived cells phenocopies the key aspects of systemic instigation (i.e., outgrowth of indolent tumors and development of stromal desmoplasia). This suggested that the formation of the myofibroblasts might well arise through the GRN-induced transdifferentiation of existing fibroblasts residing in the tumor stroma or in adjacent normal tissue. Accordingly, we set up a series of cell culture experiments to examine the effects of human rGRN on human mammary stromal fibroblasts.
GRN in vitro for a period of 6 days and then mixed them with responder cells in a ratio of 1:1 prior to injection into host mice. As a control, we made preparations of these fibroblasts that had been exposed to PBS and injected an admixture of these control fibroblasts and responding tumor cells. We then evaluated responding tumor formation and histopathology 2 weeks after injection of these tumor/fibroblast admixtures.

We observed that fibroblasts activated ex vivo by GRN exposure subsequently enabled formation of responding tumor foci that histopathologically resembled neoplastic breast tumors (Figure 6C). Within these masses, the responding tumor cells were indeed proliferative, as indicated by staining for the LgT (expressed exclusively by the tumor cells) and the proliferation marker Ki67 (Figure 6C). In contrast, normal mammary fibroblasts exposed ex vivo to PBS and then admixed to responder cells prior to implantation yielded disorganized masses, with significantly fewer proliferating tumor cells (Figure 6C). In vitro studies of tumor responder cells cocultured with GRN-activated fibroblasts did not mimic these in vivo phenomena and did not induce responder cell proliferation (Supplemental Figure 6).

Collectively, these analyses indicate that instigating GRN-expressing Sca1` cKit` hematopoietic cells recruited to sites in which responding tumor cells reside function to induce a local inflammatory response and remodel the extracellular milieu through paracrine interactions with resident fibroblasts. The resulting transdifferentiation of the latter into myofibroblasts appears to contribute in a major way to enabling the growth of tumors that would otherwise remain indolent.

GRN expression is correlated with aggressive tumor subtypes and poor survival of breast cancer patients. In the context of cancer pathogenesis, GRN has been described as an autocrine growth factor that is expressed by tumor epithelial cells and enhances tumorigenicity in vitro and in vivo (38–42). Nevertheless, the consequences of GRN expression and its relevance to breast cancer tumor types and patient survival have been unclear.

Accordingly, we analyzed GRN expression in tissue microarrays (TMA) assembled from tumors arising in a cohort of 144 patients diagnosed with breast cancers of various grades, stages, receptor status, and subtypes (Supplemental Table 1). To do so, we used 3 different antibodies to GRN protein: CAB019394, HPA028747, and HPA008763. HPA antibodies were specifically generated and used for protein profiling as part of the Human Protein Atlas effort (http://www.proteinatlas.org) (43). All tissues were analyzed in a blinded fashion with nonbiased acquisition of expression results. For each antibody, we performed CellProfiler image analysis to calculate the total area of each tissue section that was occupied by high GRN staining (highest intensity of positive GRN staining; Supplemental Figure 7).

The absolute values of GRN staining area among the 3 different antibodies, while not identical, were in good agreement (Supplemental Figure 8A). Statistical analyses revealed that the extent of high GRN staining was positively correlated with tumor size ($P < 0.038$) for all 3 antibodies and with grade for 2 of the 3 antibodies ($P < 0.001$), but not with nodal stage for any of the antibodies tested (Table 2 and Supplemental Figure 8B). GRN expression was also significantly correlated with histological and molecular subtypes of breast cancer. Specifically, high GRN expression negatively correlated with the luminal A subtype and positively correlated with triple negative and basal-like breast cancer subtypes for all 3 of the antibodies we tested (Table 2 and Supplemental Figure 8B).

Further analysis of the tissues stained with the HPA028747 antibody indicated that high GRN expression was positively correlated with the proliferation index, as indicated by Ki67 positivity ($P = 0.001$), while being negatively correlated with ER ($P = 0.004$) and PR status ($P = 0.017$; Table 2). GRN expression was strongly correlated with the triple-negative/basal-like breast tumor subtypes ($P = 0.001$; Table 2). In fact, 100% of the triple-negative/basal-like tumors expressed high GRN levels, while only 16% of the luminal tumors displayed similar levels of GRN expression (Figure 7A). In this case, breast cancer patients with tumors that were positive for GRN staining showed significantly worse outcome in overall survival (HPA028747, $P = 0.038$; Figure 7B). Together, these observations are in accord with reports that patients with triple-negative tumors have worse outcome, distinctive patterns of relapse, and reduced survival (44–46).

Discussion

The importance of the tumor microenvironment has been appreciated for at least 5 decades (47), and it is now widely accepted that many of the tumor microenvironmental components, notably the stromal fibroblasts and myofibroblasts, actively support tumor growth and progression (reviewed in ref. 48). The formation of stromal desmoplasia involving the presence of αSMA` myofibroblasts and collagen deposition is a critical event in carcinoma progression and an important prognostic indicator of metastatic disease in cancer patients (13, 49–51). The origins of these CAFs and myofibroblasts have been unclear. Some studies of preclinical animal models and of human cancer patients have implicated the resident fibroblasts in the tissues in which tumors arise (52). Yet others have indicated transdifferentiation of other tissue cell types (17, 23, 53) or the recruitment and subsequent differentiation of circulating or BM-derived cells (22, 54–57). In the present case, repeated observations indicate a local origin of these functionally critical cells, most likely involving the transdifferentiation of resident fibroblasts into myofibroblasts.

Perhaps the most surprising aspect of the instigation process has come from our discovery that the composition of the tumor stroma, in particular the accumulation of tumor-supportive myofibroblasts and the resulting stromal desmoplasia, can be induced in a systemic fashion. These observations indicate that the cellular composition of a tumor is not dictated exclusively by the neoplastic cells themselves. Instead, systemic endocrine signals such as OPN (9) can act upon the BM to exert strong influences on the histopathology and composition of stroma in tumors at distant anatomical sites (Figure 8).

Our findings are in agreement with and extend a recent report of a “proinflammatory signature” expressed by CAFs in experimental models of pancreatic and mammary adenocarcinoma and correlate with genes expressed in human squamous, breast, and pancreatic cancers; however, the study did not reveal the identity of the cells responsible for promoting the proinflammatory fibroblast signature (37). Here, we demonstrate that Sca1` cKit CD45` hematopoietic cells that are activated in the BM and recruited to responding tumors are responsible for inducing proinflammatory and matrix remodeling genes in tissue fibroblasts through their secretion of GRN. The precise signaling pathways by which GRN activates proinflammatory and matrix remodeling genes in responding tumor fibroblasts are still unknown, as the cognate cell-surface receptor for GRN has not yet been identified (30). The present observations of in vitro cocultures imply that CAFs express the GRN receptor, which may enable its identification.
Very little is known about native Sca1+cKit− cells that reside in the BM; primitive Lin-Sca1+cKit− cells have been described previously as a "mystery population" of hematopoietic cells with debatable marrow-reconstituting capacity and a marked resistance to the cytotoxic effects of 5-FU (25, 26). Other reports suggest that some subsets of Sca1+cKit− cells represent lymphoid-biased progenitors that do not yet display terminal deoxyribonucleotide transferase or Rag1/2 recombinease activity, while other subsets can give rise to myeloid lineages under certain conditions (27, 28). More recently, Lin Sca1+cKit− BMCs have been reported to give rise to all hematopoietic lineages in response to Wnt3a stimulation (29).

Although our analysis of other commonly studied cell-surface antigens expressed by the Sca1+cKit− BMCs did not reveal differences between instigator- and noninstigator-bearing mice, we noted that expression of the FcγRI — normally expressed on some macrophages, neutrophils, eosinophils, and dendritic cells — was significantly upregulated in our instigating Sca1+cKit− population (GEO GSE25620). It was recently reported that FcγRI-positive cells are necessary, in a B cell–dependent manner, for malignant progression in a mouse model of squamous carcinogenesis (58). In fact, nude mice like those used in our studies (Ncr-FoxN1tm) do have small numbers of T cell precursors in their BM, mature B cells, mature NK cells, and cells of the myeloid lineages (59, 60). Nevertheless, the relationship between these reported FcγRI cells and the GRN-expressing Sca1+cKit− hematopoietic cells that we have observed remains to be determined.

We also found large numbers of GRN-expressing BM-derived hematopoietic cells in the responding tumor stroma at early and late stages of responding tumor development, indicating that these BMCs are either continuously recruited or that they persist within the responding tumor mass following their recruitment. Moreover, at present, we do not know the fate of the instigator-activated Sca1+cKit−CD45+ hematopoietic BMCs once they take up residence in the responding tumor stroma. However, importantly, the activated GRN-expressing BMCs recruited into responding tumors do not directly give rise to the tumor-associated myofibroblasts; instead, they mediate stromal activation and facilitate the acquisition of malignant traits in the responding tumor microenvironment.

GRN is correlated with increased malignancy in a number of different cancer types and has been reported to augment tumor cell proliferation in vitro and in vivo (reviewed in ref. 30). A number of reports have demonstrated that GRN is expressed in tumor epithelium as well as tumor stromal compartments (41, 61–64). Indeed, our own survey of tumors from human breast cancer patients revealed areas of GRN staining within the epithelium and the tumor stroma. While these studies do not reveal the precise source of GRN, it is clear that high GRN expression is significantly associated with the most aggressive breast tumor subtypes and reduced patient survival.

Our work sheds light on a cascade of events with clinically relevant consequences that has been poorly understood — the formation of desmoplastic stroma and malignant growth of otherwise indolent tumors. Noting that the activity of GRN-expressing BMCs is unique to the marrow of hosts bearing instigating tumors, we speculate that effective anticancer therapies might involve targeting GRN or the activated BM-derived hematopoietic cells that express GRN, thereby disrupting these lines of communication that promote cancer progression.

## Methods

### Cell lines

Generation of HMLER hygro-H-rasV12 (responders) and BPLER human mammary epithelial tumor cells (instigators) has been described (9). Human mammary carcinoma MDA-MB-231 (instigators), MDA-MB-436 (noninstigators), and human prostate carcinoma PC3 (noninstigators) were obtained from ATCC and cultured under standard conditions. SUM149 (noninstigators) were provided by Stephen Ethier (University of Michigan, Ann Arbor, Michigan, USA) and grown as described (65).

### Animals and human tumor xenografts

Female nude mice were purchased from Taconic; Rag1−/−xEGFPTg mice were previously described (9). All experiments were performed in accordance with regulations of Children's Hospital animal care protocol (09-12-1566) and MTT Committee on Animal Care protocol (1005-076-08). All animal studies were approved by the Children's Hospital Boston (CHB) Animal Care and Use Committee (Boston, Massachusetts). Tumor cells were suspended in 20% Matrigel (BD Biosciences) and injected subcutaneously into nonirradiated mice; tumor diameter was periodically measured on the flanks of live nude mice using calipers; volume was calculated as 4/3πr³. For systemic instigation experiments, cells were injected contralaterally beneath the skin of nonirradiated recipient mice as follows: 2.5 × 10⁵ HMLER hygro-H-rasV12 was transplanted into the left flank, while 10⁵ GFP+BPLER, 2.5 × 10⁵ GFP+BPLER, 10⁴ MDA-MB-231 (instigators), or 2 × 10⁵ PC3 (noninstigator) was inoculated in to the right flank.

For experiments to test function of BMCs, BM was harvested from indicated tumor-bearing mice (described below), and either whole BM or FACS-sorted populations were mixed with 2.5 × 10⁵ HMLER hygro-H-rasV12–responding tumor cells, suspended in 20% Matrigel, and injected subcutaneously into nude mice as previously described (13). The following numbers of BMCs were used: 7.5 × 10⁶ whole BMCs, 7.5 × 10⁵ Sca1+cKit− cells, 7.25 × 10⁵ Sca1-depleted cells, or 2.5 × 10⁴ Sca1+cKit− cells.

### Immunofluorescence and immunohistochemistry

Dissected tumors were fixed in 4% (w/v) paraformaldehyde 16–18 hours, embedded in paraffin, and sectioned onto ProbeOn Plus microscope slides (Fisher Scientific) for immunohistochemistry or immunofluorescence as described (13). Primary antibodies were as follows: anti-αSMA (1:75, Vector Labs), anti-Ki67 (1:50; BD Biosciences), anti-Sca1 (1:50; BioLegends), anti-GFP (1:400, Abcam), and anti-GRN (1:50, R&D Systems). Secondary antibodies were as follows: FITC–anti-goat IgG (1:100, Abcam), Alexa Fluor 488 anti-goat IgG (1:200; Invitrogen), Alexa Fluor 488 anti-rat IgG (1:200; Invitrogen), Alexa Fluor 488 and 594 anti-mouse IgG (1:200; Invitrogen), and Alexa Fluor 594 anti-rabbit IgG (1:200; Invitrogen). Vectastain Elite ABC system kits were used for IHC (Vector Laboratories).

### BM harvest and transplantation

BMCs were harvested from donor mice as previously described (13). Briefly, femurs and tibias were isolated and flushed with sterile HBBS (Gibco) with penicillin/streptomycin/fungosone. Cells were washed 2× with sterile HBBS, dissociated with 18-gauge needles, and filtered through 70-μm nylon mesh. For transplantation experiments, 2 × 10⁶ BMCs from Rag1−/−xEGFPTg donor mice were injected into the retroorbital sinus 8–10 hours after irradiation of recipient mice (6 Gy). Antibiotics were added to drinking water for 14 days following the procedure. At the end of each experiment, recipient mice were anesthetized by i.p. injection of Avertin and vasculature was exanguinated by perfusion of sterile PBS through the left ventricle.

### Flow cytometry and FACS

Freshly harvested tissues were digested in 1 mg/ml collagenase A for 1–4 hours at 37°C with continuous rotation. Resulting cell suspensions were dispersed with an 18-gauge needle, washed 2× with Resuspension Buffer (2% heat-inactivated FCS in sterile HBBS), and filtered through 70-μm nylon mesh. Single-cell suspensions were prepared for flow cytometry by suspension in PBS containing 2% FCS and 0.01% NaN₃, labeled with appropriate antibodies for 30 minutes at 4°C, acquired on a FACSCanto II (FACSDiva software 5.02; BD Biosciences), and ana-
lyzed using FlowJo software (Tree Star, Inc.). Dead cells were excluded using Live/Dead Fixable Aqua cell stain (Invitrogen). In some cases, samples were blocked with an antibody to CD16/CD32 Fcy III/II receptor (250 ng/10⁶ cells; BD Pharmingen). Antibodies used for flow cytometry were as follows: PE-cy5-anti-ly-6A/E/Sca-1 (clone D7; eBioscience), PE-anti-CD117/c-KIT (28B, eBioscience), APC-Alexa 780-anti-CD45 (30-F11; eBioscience), Pacific blue-anti-CD11b/Mac-1 (M1/70; eBioscience), PE-Cy7-anti-Gr1 (RB6-8C5; eBioscience), FicT-anti-NK1.1 (NK1.1, NKR-P1c, Ly-55; eBioscience), APC-anti-CD11c (Integrin alpha x, p150/90; eBioscience), APC-anti-VEGFR1/Flt1 (141S22; eBioscience), Alexa Fluor 647-goat anti-rabbit; Alexa Fluor 647-goat anti-rat (200 ng/10⁶ cells; Molecular Probes); and mouse lineage panel kit (BD Biosciences — Pharmingen). FACs antibodies were as follows: PE-anti-Ly-6A/E/Sca-1 (400 ng/10⁶ cells; clone E13-161.7; BD Biosciences — Pharmingen); APC/PE-anti-CD117/c-KIT (400 ng/10⁶ cells; clone 2B8; BD Biosciences — Pharmingen).

RNA preparation, gene expression array, and computational analyses. BMCs were treated as follows: Sca1+cKit– BMCs were isolated by FACS directly from bone marrow aspirates or by an in vitro expansion protocol. Gene expression profiling of Sca1+cKit– BMCs from mice was performed as previously described using the Affymetrix MG-430A microarrays. Immunofluorescence analysis was performed on Affymetrix MG-430A microarrays. Fibroblasts were treated as follows: triplicate samples of the human fibroblast cell line hMF-2 were cultured in the presence of 1 μg/ml of recombinant human GRN (R&D Systems) or 250 ng/ml or 1 μg/ml of recombinant human TGF-ß1 (R&D Systems) or 250 ng/ml or 1 μg/ml of recombinant human GRN (R&D Systems) for a duration of 6 days. Immunofluorescence analysis of αSMA expression was performed as previously described using Cy3-conjugated anti-αSMA antibody (Sigma-Aldrich) (70).

Human tissue specimens and TMA. Ethical approval for the use of breast cancer specimens for this study was obtained from the Ethics Committee at Lund University (ref no 447-07), whereby written consent was not required and patients were offered the option to opt out. The specimens used in this study were obtained from 144 patients diagnosed with breast cancer at the Department of Pathology, Malmö University Hospital (Malmö, Sweden) between 2001 and 2002. The median age at diagnosis was 65 years (range 34–97), and the median follow-up time for disease-specific and overall survival was 78 months. 21% of all patients in this cohort had received adjuvant chemotherapy. All tissue cases were histopathologically reevaluated on slides stained with H&E prior to TMA construction. Representative areas were marked and the TMA was constructed as described previously (71, 72). Cores of 1 mm for 144 individual breast tumors, in duplicates, were used for creating the TMA. Primary antibodies used for GRN staining of TMA included HPA028747 (1:100; AtlasAntibodies), HPA008763 (1:50; AtlasAntibodies), and CAB019394 (1:600; Strategic Diagnostics). Automated immunohistochemistry (Autostainer 480; Lab Vision) was performed as previously described (73).

GRN ELISAs. Murine plasma was collected as described (13). Murine GRN levels were measured by quantitative sandwich assay using anti-GRN primary antibody (#MAb25571 clone 333731; 4 μg/ml) and biotin-conjugated secondary antibody (BAF2557; 1 μg/ml; R&D Systems) according to standard protocols.

GRN mRNA expression. RNA was extracted from sorted Sca1+cKit– cells by RNeasy Micro Kit (QIAGEN). Reverse transcriptase and preamplification were done by the High Capacity cDNA Reverse Transcription Kit and TaqMan PreAmp (ABI), respectively. Quantitative PCR (qPCR) analysis was assessed by ABI-7300, and GRN expression was calculated relative to housekeeping genes. Probe numbers were as follows: B2M (Mm00437762_m1*); Actb (Mm01205647_g1); and GRN (Mm00433848_m1*).

Statistics. For human TMA data, χ² and Spearman’s correlation tests were used for comparison of protein expression and patient and tumor characteristics. All statistical tests were 2 sided; P < 0.05 was considered significant. Log-rank test were used for Kaplan-Meier analysis. All statistics were performed using IBM SPSS Statistics 18.0 (SPSS Inc.). Unless otherwise specified, all other data are expressed as mean ± SEM, and data analyzed by Student’s t test were considered statistically significant if P < 0.05.

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