Delineation of a Cellular Hierarchy in Lung Cancer Reveals an Oncofetal Antigen Expressed on Tumor-Initiating Cells

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Abstract

Poorly differentiated tumors in non–small cell lung cancer (NSCLC) have been associated with shorter patient survival and shorter time to recurrence following treatment. Here, we integrate multiple experimental models with clinicopathologic analysis of patient tumors to delineate a cellular hierarchy in NSCLC. We show that the oncofetal protein 5T4 is expressed on tumor-initiating cells and associated with worse clinical outcome in NSCLC. Coexpression of 5T4 and factors involved in the epithelial-to-mesenchymal transition were observed in undifferentiated but not in differentiated tumor cells. Despite heterogeneous expression of 5T4 in NSCLC patient–derived xenografts, treatment with an anti-5T4 antibody–drug conjugate resulted in complete and sustained tumor regression. Thus, the aggressive growth of heterogeneous solid tumors can be blocked by therapeutic agents that target a subpopulation of cells near the top of the cellular hierarchy. Cancer Res; 71(12): 4236–46. ©2011 AACR.

Introduction

Non–small cell lung cancer (NSCLC) is the leading cause of cancer-related deaths, due to high incidence and lack of effective therapies (1). NSCLC has heterogeneous pathologies and molecular profiles, which presents challenges to molecular targeting and treatment (2–4). The degree of tumor cell differentiation is an independent prognostic factor for clinical outcome, as less differentiated tumors are associated with increased risk of death in both squamous cell carcinoma and adenocarcinoma (5). Strikingly, less differentiated tumors are also associated with increased risk of recurrence after resection (5). The molecular and cellular bases for these associations are not understood.

Investigation of the cellular heterogeneity in tumors has encouraged new frameworks, such as the cancer stem cell hypothesis, for understanding the cellular hierarchy as it relates to disease progression and for designing therapeutic strategies (6–8). These experiments have shown that capacities for self-renewal and differentiation vary among cells in a given tumor. The types and relative proportions of various cell subpopulations in solid tumors are likely major determinants of disease progression and therapeutic responsiveness in cancer patients. In many cases, only certain subpopulations of cancer cells from a tumor can initiate tumor growth in immunodeficient mice. Herein, these cells are referred to as tumor-initiating cells (TIC); they are also known in the literature as cancer stem cells and cancer-initiating cells (6–8). TICs have been isolated, enriched, or identified in tumors of brain, breast, colon, and head and neck, lung, melanocytes, pancreas, prostate, and the hematopoietic system, typically with antibodies against cell surface markers (9). In general, the tumors grown from TICs recapitulate the cellular heterogeneity of the original tumor, which underscores the developmental plasticity of many TICs and the differentiation hierarchy in many tumor tissues.

Tumor cell subpopulations and their distinct roles in disease progression can be studied using a variety of complementary approaches (8). The isolation of defined cell subpopulations from tumors, xenografts, and established cell lines based on cell surface markers allows for an in-depth molecular analysis of rather homogeneous subpopulations. The culturing of cancer cells in defined serum-free media and/or 3-dimensional (3D) matrices has been shown to maintain karyotype, transcriptome, and signaling that are reflective of the tissue of origin (10, 11). Patient-derived xenografts (PDX)
are established directly from freshly resected tumors and exhibit rich architectures that reflect the original patient tumors. PDXs are complex yet tractable preclinical models that can be used to study cellular heterogeneity and evaluate the efficacy of therapeutic agents.

Here, we apply these emerging frameworks and technologies to delineate a cellular hierarchy in NSCLC and apply the new knowledge to drug discovery. By integrating novel experimental models of NSCLC with the clinicopathologic analysis of patient tumors, we identify the 5T4 oncofetal antigen as a marker of undifferentiated, highly tumorigenic cells and of worse clinical outcome. We show preclinical efficacy of an anti-5T4 antibody–drug conjugate (ADC) and suggest that this therapeutic strategy could be applied to other surface markers expressed on TICs.

Materials and Methods

Isolation and serum-free culture of human lung tumor cells

Human lung tumor tissue (sample 87426A1) was obtained from Asterand in accordance with appropriate consent procedures, washed in PBS, and minced. Fragments were disaggregated with collagenase III (250 U/mL) at 37°C for 2 to 3 hrs. Partially digested tissue fragments were passed through steel mesh screens. Cells were sieved through a 40-µm cell strainer (BD Falcon) and treated with red blood cell lysis buffer (Roche). Dead cells were excluded by magnetic separation (Miltenyi Biotec). The culture was established and maintained in serum-free bronchial epithelial cell growth medium (BEGM; Lonza), which was changed 50% every other day.

Air–liquid interface cultures

Millicell 1-µm PET hanging cell culture inserts (Millipore) were seeded with 2.5 × 10^5 cells from sample 87426A1 culture. After 1 to 2 days, the upper and lower chambers were rinsed with PBS, and CnT-23 medium (CELInTec) containing 50 mmol/L retinoic acid and 1 mmol/L CaCl₂ was added only to the lower chamber, leaving cells exposed to the air. Lifted cultures were fed every other day with fresh medium or harvested in Buffer RLT (Qiagen) for RNA isolation or TBS/0.5% NP-40 for immunoblot analysis. For gene expression profiling, "undifferentiated" values are averages of triplicate samples, and "differentiated" values, due to limited sample, were averaged from differentiation time points of 8, 16, and 24 days.

Animal studies

All animal studies were approved by the Pfizer Pearl River Institutional Animal Care and Use Committee according to established guidelines. To assess tumorigenic potential of sorted cells, the cells were implanted in 50% Matrigel or where noted, 50% growth factor–reduced Matrigel (BD Biosciences) subcutaneously between the shoulder blades. 60257A1 cells were implanted in NOD-SCID (severe combined immunodeficient) mice and tumor incidence was recorded after 9 weeks. For H460T and HCC2429, 100 sorted cells were implanted per nu/nu mouse. Tumors were measured at least once a week with tumor volume = 0.5 × width^2 × length. The P values are based on 2-sided Student’s t test. Efficacy studies are described in Supplementary Information.

Clinical samples

This study was approved by the MD Anderson Institutional Review Board. Tissue specimens were collected between 1997 and 2002 from 320 lung cancer tumors (204 adenocarcinomas and 116 squamous cell carcinomas), and selected specimens were used for construction of tissue microarrays. The primary antibodies used for immunohistochemistry were mouse monoclonal anti-CD24 (Clone SN3b; LabVision), rabbit polyclonal anti-CD44 (Sigma), and mouse monoclonal anti-5T4 (MAB4975, R&D Systems). The statistical analysis was based on membrane expression levels as described in Supplementary Data.

Additional Materials and Methods can be found in the Supplementary Data.

Results

A cell line model reveals 5T4 expression in TICs

To identify a model of tumor heterogeneity in NSCLC, we screened several cell lines for heterogeneous expression of cell surface markers that had previously been used to enrich or isolate TICs (6, 9). Staining of the H460T cell line with anti-CD24 and anti-CD44 antibodies revealed distinct subpopulations of cells with a stable distribution over many passages in culture (Fig. 1A and data not shown). The delineation between CD24^-/loCD44^-/hi combination of surface markers gave rise to less tumorigenic CD24^hiCD44^lo cells (Supplementary Fig. S1 and data not shown). Together these results showed that the 5T4 oncofetal antigen is a marker of undifferentiated, highly tumorigenic cells and of worse clinical outcome. To determine whether these subpopulations had different tumorigenic capacities, we isolated cells of each subpopulation by fluorescence-activated cell sorting (FACS) and implanted them subcutaneously into immunocompromised mice. CD24^-/loCD44^-/hi cells formed small tumors rapidly, whereas CD24^-/hiCD44^-/lo cells exhibited slower tumor growth (P < 0.001; Fig. 1B). Tumors from CD24^hiCD44^lo cells were also larger than tumors from CD24^-/loCD44^-/hi cells (P < 0.02; Supplementary Fig. S1A). In vitro, CD24^-/loCD44^-/hi cells migrated more efficiently than CD24^-/hiCD44^-/hi cells and exhibited multipotency in that they gave rise to less tumorigenic CD24^-/hiCD44^-/lo cells (Supplementary Fig. S1 and data not shown). Together these results indicated that the CD24^-/loCD44^-/hi combination of surface markers enriched for TICs in H460T. Similar results were observed for another NSCLC cell line, HCC2429 (data not shown).

To study the clinical relevance of these results, we examined CD24 and CD44 expression in patient samples. By immunohistochemistry, CD24^-/loCD44^-/hi membrane expression was associated with less differentiated tumor histology (P = 0.0456). CD24^-/loCD44^-/hi membrane expression was also associated with worse overall survival in male squamous cell carcinoma (P = 0.0310; Supplementary Fig. S2A). In addition, analysis of published mRNA data (12) revealed that CD24^-/loCD44^-/hi was associated with worse overall survival in adenocarcinomas (P = 0.0501; Supplementary Fig. S2B). Taken together, these results showed that the...
TIC markers identified in H460T and HCC2429 were also poor prognosis markers in NSCLC, which indicates the clinical relevance of the cell line models.

From a therapeutic perspective, it is not feasible to target the $\text{CD24}^{+}/\text{CD44}^{lo}$ combination of markers. Therefore, we sought to identify novel TIC markers in NSCLC that could be potential therapeutic targets. We generated gene expression profiles from triplicate samples of sorted $\text{CD24}^{+}/\text{CD44}^{lo}$ and $\text{CD24}^{hi}\text{CD44}^{hi}$ cells from H460T (Supplementary Fig. S1E). The $\text{5T4 (TPBG)}$ gene had significantly higher expression in the more tumorigenic $\text{CD24}^{+}/\text{CD44}^{lo}$ cells than in the $\text{CD24}^{hi}\text{CD44}^{hi}$ cells (Fig. 1C and Supplementary Table S1). Consistent with this result, in NSCLC clinical samples, 5T4 mRNA expression was significantly higher in $\text{CD24}^{+}/\text{CD44}^{lo}$ versus "Not $\text{CD24}^{+}/\text{CD44}^{lo}$" tumors (ref. 12; $P = 0.0293$; Supplementary Fig. S2C).

5T4 is a single-pass transmembrane protein that is preferentially expressed in many tumor types compared with normal tissues (13) and has been explored as a cancer target. During embryonic development, 5T4 functions in epithelial-to-mesenchymal transition (EMT) and cell migration, at least in part by interacting with CXCR4 and/or the actin cytoskeleton (14–17). Given the oncofetal characteristics of 5T4 and its increased expression in the tumorigenic $\text{CD24}^{+}/\text{CD44}^{hi}$ subpopulation of H460T, we focused on 5T4 as a potential TIC marker in NSCLC.

Immunofluorescence studies in H460T revealed that staining for 5T4 and CD24 were mutually exclusive, consistent with the gene expression data, and moreover that most if not all $\text{CD24}^{+}/\text{CD44}^{lo}$ cells expressed 5T4 (Fig. 1D). This result was extended by flow cytometric (Supplementary Fig. S3) and immunoblot analysis (Fig. 1E).

On the basis of the expression of 5T4 in normal progenitor cells during embryonic development (18), we hypothesized that 5T4 expression is associated with a less differentiated state and that inducing differentiation of tumor cells would reduce 5T4 expression. Sorted cells were treated with retinoic acid and subjected to immunoblot analysis. Indeed, 5T4 expression was dramatically reduced in treated $\text{CD24}^{+}/\text{CD44}^{hi}$ cells (Fig. 1E).

To test tumorigenicity based on 5T4 expression, we sorted cells from a clonal line of H460T and implanted them into mice. As predicted, $\text{5T4}^{hi}$ cells were more tumorigenic than $\text{5T4}^{lo}$ cells ($P < 0.03$; Fig. 1F), which indicated that 5T4 can...
independently enrich for TICs in this system. On the basis of all of these results, we sought to further establish 5T4 as a novel TIC antigen by using PDXs.

**5T4 enriches for tumorigenicity in a PDX**

We established NSCLC PDX lines by implanting fragments of freshly resected tumors (squamous cell carcinoma) subcutaneously in immunocompromised mice. Each line was propagated by explanting xenograft fragments into naive animals and was maintained exclusively in vivo. In each PDX line, the histology of the xenograft resembled that of the original tumor (data not shown).

To determine whether 5T4 expression enriched for tumorigenic capacity in PDXs, 5T4hi and 5T4lo cells were sorted from dissociated 60257A1 PDXs and implanted into animals. Cells from this PDX line exhibited a wide continuous range of 5T4 expression levels, and the highest and lowest 15% were assigned 5T4hi and 5T4lo (Fig. 2A). 5T4hi cells yielded substantially higher tumor incidence than 5T4lo cells in 3 independent experiments (Table 1). On the basis of limiting dilution analysis, 5T4hi cells were about 30-fold more tumorigenic than 5T4lo cells. Thus, the results in the PDX are consistent with those previously (19), the experiment was repeated 2 additional times in regular Matrigel. The tumorigenicity of 5T4hi cells when implanted in 50% growth factor–reduced Matrigel (Table 1). To determine whether tumorigenicity was dependent on growth factors, as reported previously (19), the experiment was repeated 2 additional times in regular Matrigel. The tumorigenicity of 5T4hi cells was slightly enhanced in these conditions but was still significantly lower than that of 5T4lo cells (Table 1). Tumors that grew from sorted 5T4hi cells showed heterogeneous 5T4 expression (Fig. 2B). Thus, the results in the PDX are consistent with those from H460T and show that 5T4hi expression can enrich for TICs in NSCLC.

To uncover molecular differences between 5T4hi and 5T4lo cells, we generated gene expression profiles from cells sorted on 3 independent occasions from 60257A1. Strikingly, the Clara cell secretary protein (CCSP, also known as uro-oglobin, SCGB1A1) was expressed 20-fold higher in 5T4hi than in 5T4lo cells (Fig. 2C). CCSP has been characterized as a marker of lung stem cells in normal tissue and adenocarcinoma (20). In addition, several genes associated with tumorigenesis, invasion, and stem cells were expressed at higher levels in 5T4hi cells including carcinoembryonal antigens CEACAM6 and CEACAM1, cathepsin S (CTSS), gelsolin (GSN), and interleukin (IL) 8 (Fig. 2C). In contrast, low levels of CD133 were comparable in both populations (Supplementary Fig. S4A). In summary, the gene expression profiles distinguished the 5T4hi and 5T4lo populations and offered potential explanations for their different tumor-initiating capacities.

**5T4 and markers of EMT are expressed in cells near the top of the tumor hierarchy**

Immunohistochemical analysis of our PDXs revealed a range of 5T4 expression levels and patterns. Three of 6 PDX lines exhibited heterogeneous expression of 5T4, and in 2 of the 3, 5T4 expression was coupled to tumor architecture in that expression was higher at the tumor–stroma interface (Fig. 3A and B and Supplementary Fig. S4B). Notably, in 37622A1, a pattern similar to 5T4 was observed for vimentin, a marker of EMT, and Ki67, a proliferation marker (Fig. 3A). Coimmunostaining confirmed that 5T4hi cells were typically positive for Ki67 in this PDX line (Fig. 3B).

When a serum-free culture was established from the 37622A1 PDX (Fig. 3C), the cells exhibited uniformly high 5T4 expression, whereas the PDX exhibited a broader expression range (Fig. 3D). Because the culture media supports growth of undifferentiated cells, this result was consistent with the hypothesis that 5T4 is highly expressed on TICs. Strikingly, when the cultured cells were implanted into animals, the resulting tumors exhibited heterogeneous 5T4 expression (Fig. 3E and Supplementary Fig. S4C). This result suggested that 5T4hi cells gave rise to 5T4lo cells during tumor growth by a mechanism that potentially requires tumor–stroma interaction or other microenvironmental cues.

To further investigate the cellular hierarchy in NSCLC, we developed a novel 3D model of lung cancer differentiation. In a serum-free culture established directly from freshly resected tumor (sample 87426A1), cells could either be maintained in the undifferentiated state submerged in stem cell media or be induced to differentiate at the air–liquid interface with retinoic acid but notably without the use of serum (Fig. 4A). The air–liquid interface is considered a physiologic environment for lung cells and used to study differentiation of immortalized bronchial epithelial cells (21). The 87426A1 culture efficiently formed a 3D multilayered epithelium on exposure to the air–liquid interface for 18 days (Fig. 4B).

Immunoblot analysis showed that 5T4 levels were high in the undifferentiated state and decreased quickly and dramatically on differentiation (Fig. 4C). This result was analogous to retinoic acid treatment of sorted H460T cells (Fig. 1E).

To obtain a global view of the cellular hierarchy in NSCLC, gene expression profiles were generated from undifferentiated and differentiated cells. Consistent with the above results, 5T4 expression decreased and CD24 expression increased during differentiation (Fig. 4D and E). These data were confirmed by flow cytometry (Supplementary Fig. S5). The profiles revealed striking patterns of genes involved in EMT and angiogenesis. The EMT markers vimentin, fibronectin, Slug, and Twist were expressed at significantly higher levels in undifferentiated cells (Fig. 4D); in contrast, the epithelial differentiation markers mucin and involucrin as well as transglutaminase (TGM) and cytokeratins were expressed at significantly higher levels in differentiated cells (Fig. 4E). The coexpression of 5T4 and vimentin in undifferentiated cells was consistent with the similar expression patterns of 5T4 and vimentin in 37622A1 PDX (Fig. 3A). Interestingly, angiogenesis factors, including VEGF-A, VEGF-C, PDGF-A (platelet-derived growth factor), PGF (placental growth factor), and uPA (urokinase-type plasminogen activator), were expressed at significantly higher levels in differentiated cells (Fig. 4F). These results are noteworthy given the higher 5T4 expression at the tumor–stroma interface in 2 of our 6 PDX lines.

An unbiased meta-analysis revealed several gene signatures with significant expression changes during differentiation (Supplementary Table S2). Gene sets with higher expression in undifferentiated cells included signatures of poor clinical...
Figure 2. 5T4 can enrich for TICs in NSCLC. A, 5T4 expression in the 60257A1 PDX. See Table 1 for tumor incidence of the cell subpopulations. B, immunohistochemistry of 5T4 in tumors that grew from 5T4hi cells sorted from 60275A1. C, mRNA signal intensities on gene microarrays probed with samples from 5T4hi or 5T4lo cells sorted from PDXs on 3 independent occasions. Values indicate the mean ± SD.
Table 1. Tumor incidence in animals implanted with 5T4\textsuperscript{hi} or 5T4\textsuperscript{lo} cells sorted from 60257A1 PDXs in 3 independent experiments

<table>
<thead>
<tr>
<th>No. of cells</th>
<th>Growth factor-reduced Matrigel (Expt. 1)</th>
<th>Matrigel (Expt. 2; Expt. 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5T4\textsuperscript{hi} cells</td>
<td>5T4\textsuperscript{lo} cells</td>
</tr>
<tr>
<td>500</td>
<td>10% (1/10)</td>
<td>n.d.</td>
</tr>
<tr>
<td>1,500</td>
<td>20% (2/10)</td>
<td>0% (0/10)</td>
</tr>
<tr>
<td>5,000</td>
<td>62% (5/8)</td>
<td>0% (0/10)</td>
</tr>
<tr>
<td>15,000</td>
<td>n.d.</td>
<td>11% (1/9)</td>
</tr>
</tbody>
</table>

Abbreviation: n.d., not determined.
prognosis, stem cells, oncogenic signaling, and developmental
signaling. Gene sets with higher expression in differentiated
cells included signatures of good clinical prognosis, differen-
tiated tumors, and differentiated cells. Taken together, these
results show a cellular hierarchy in a primary NSCLC culture
and support the concept that less differentiated tumor cells
can have a more malignant phenotype.

Correlation between 5T4 expression and
clinicopathologic features and disease outcomes

We sought to determine whether 5T4 expression in NSCLC
tumors correlated with clinicopathologic features and disease
outcomes. In a panel of surgically resected tumors, 5T4
expression levels and patterns varied, and each sample was
assigned an overall score. The distribution of 5T4 expression

Figure 4. 5T4 and markers of EMT
are associated with the
undifferentiated state. A,
schematic of serum-free culture
under conditions that maintain the
undifferentiated state or induce
differentiation at the air–liquid
interface. B, micrographs of the
87426 A1 culture in the
undifferentiated state (left) and
after differentiation for 18 days
(right). Scale bars, 100 μm. C, 5T4
immunoblot analysis during
differentiation. D–F, mRNA signal
intensities on gene microarrays
probed with samples of
undifferentiated (undiff) and
differentiated (diff) cells. Values
represent mean ± SD.
P was associated with shorter survival time (Table S4). In addition, high membranous 5T4 expression (Table S5) and shorter time to recurrence (Fig. 5A; and 5T4 Table S5). When the cohort was stratified by 5T4 hi and P and overall ANOVA yielding P = 0.0005 and P = 0.0022; see Supplementary Table S4). Notably, membranous 5T4 expression with an anti-5T4 ADC (Fig. 6E). Treatment with calicheamicin alone, anti-CD22 calicheamicin ADC, camptothecin, 5-fluorouracil, or ionizing radiation (data not shown). These results showed the specificity of the anti-5T4 ADC.

Regression of tumors with heterogeneous 5T4 expression with an anti-5T4 ADC

We hypothesized that a therapeutic agent that targets and eliminates 5T4 hi-expressing TICs could ultimately cause regression of tumors despite heterogeneous expression of 5T4 within the tumor. The stable chemical linker between antibody and drug restricts the release of calicheamicin to cells that internalize the ADC (24). We assessed the efficacy of an anti-5T4 ADC on the growth of 2 PDX lines with heterogeneous 5T4 expression. In both lines, 5T4 expression was predominant at the tumor–stroma interface, but the overall 5T4 expression level was higher in 37622A1 than 60274A1 (Supplementary Fig. S4B and D). 37622A1 tumors harbored a K-ras G13V mutation, whereas 60274A1 tumors had wild-type K-ras (Fig. 6D and E).

PDX tumors were treated with anti-5T4 ADC, anti-CD33 ADC or vehicle; the anti-CD33 ADC served as a negative control because these PDX lines do not express CD33 (data not shown). In 37622A1, treatment with anti-5T4 ADC regressed the tumors, and no regrowth was observed even 3 months after the last dose; in contrast, treatment with anti-CD33 ADC or vehicle did not inhibit tumor growth (Fig. 6D). Similarly, in 60274A1, treatment with anti-5T4 ADC regressed the tumors despite the lower 5T4 expression in this line (Fig. 6E). Treatment with calicheamicin (not conjugated to an antibody) has not shown any significant impact on tumor growth (22, 24, 25).

In contrast to the efficacy observed with anti-5T4 ADC, treatment of both PDXs with cisplatin at the maximum tolerable dose regressed tumors only transiently and the tumors regrew after treatment was completed (Fig. 6E and Supplementary Fig. S6). These results highlight the superior long-term efficacy of an ADC that targets TICs as compared with a conventional chemotherapeutic.

Discussion

5T4 and the cellular hierarchy in NSCLC

Using an integrated strategy, we have delineated a cellular hierarchy in NSCLC and identified 5T4 as a clinically relevant marker that can enrich for TICs. We found that 5T4 expression according to clinicopathologic characteristics is shown in Supplementary Table S3. Notably, membranous 5T4 expression was higher in poorly and moderately versus well-differentiated tumors (P = 0.0005 and P = 0.0197, respectively, with overall ANOVA yielding P = 0.0022; see Supplementary Table S4). In addition, high membranous 5T4 expression was associated with shorter survival time (P = 0.0283, Fig. 5A; and P = 0.078 in multivariate analysis, Supplementary Table S5) and shorter time to recurrence (P = 0.0495, Fig. 5B; and P = 0.034 in multivariate analysis, Supplementary Table S5). When the cohort was stratified by 5T4 hi and 5T4 lo, there was no difference in the impact of patient treatment on clinical outcome (not shown). These observations are consistent with our experimental results that indicate that 5T4 is associated with less differentiated, more tumorigenic cells in NSCLC.

An ADC is specifically cytotoxic to 5T4-expressing cells

Taken together, these results provided the rationale for targeting 5T4-expressing cells with an ADC even in tumors with heterogeneous 5T4 expression. Unconjugated anti-5T4 monoclonal antibody has not exhibited any in vitro activity or in vivo efficacy (22). To generate the ADC, anti-5T4 antibody (13), previously shown to internalize into cells (22), was conjugated to the enediyne natural product calicheamicin, a DNA-damaging agent (ref. 23; Fig. 6A). To show specificity for 5T4-expressing cells, in vitro experiments were carried out on sorted H460T cells. In a proliferation assay, the 5T4enriched population was greater than 10-fold more sensitive to the ADC than the 5T4-low population (Fig. 6B). In a colony formation assay in which cells were treated with drug and then seeded at low density, the 5T4-enriched population was similarly greater than 10-fold more sensitive to the ADC than the 5T4-low population (Fig. 6C). In contrast, no difference in sensitivities was observed when the 2 populations were treated with calicheamicin alone, anti-CD22 calicheamicin ADC, camptothecin, 5-fluorouracil, or ionizing radiation (data not shown). These results showed the specificity of the anti-5T4 ADC.

Figure 5. 5T4 expression in NSCLC is associated with worse clinical outcome. A, 5T4 expression in NSCLC is associated with worse overall survival in patients. B, 5T4 expression in NSCLC is associated with shorter time to recurrence in patients.
was associated with high tumorigenic capacity and the undifferentiated state; these results parallel the expression of 5T4 in cycling progenitor cells during embryonic development (18). The association of 5T4 expression with EMT in tumors, observed in the 87426A1 serum-free culture and the 37622A1 PDX, mirrors the association of 5T4 with EMT in normal development (15). Our results are consistent with a recent study that described the relationship between EMT and stem cell phenotypes in normal and cancerous tissues (26).

Expression of 5T4 has been associated with advanced disease and/or poor prognosis in colorectal, ovarian, and gastric cancers (27–29). We found that 5T4 is associated with less differentiated tumor histology, shorter time to recurrence, and worse overall survival in NSCLC. Interestingly, although CD133 was used to isolate NSCLC TICs (30, 31) and was expressed in drug-tolerant PC9 cells (32), its expression in NSCLC was not associated with patient survival (33). On the basis of the published observation that CD133⁺ cells are quiescent (30) and our observation in a different model that 5T4hi cells are proliferating, we speculate that CD133⁺ and 5T4hi might define different TIC populations even in the same NSCLC tumor—allogeneic to the emerging evidence for distinct stem cell populations (e.g., quiescent vs. active/proliferating, in normal tissues; ref. 34). The clinical relevance of the 5T4 marker suggests that 5T4hi TICs contribute directly to one or more aspects of disease progression in NSCLC. For
instance, 5T4hi TICs may contribute to metastasis, as that process might originate when cells in a primary epithelial tumor undergo EMT (35).

The morphologic heterogeneity observed in NSCLC and other epithelial tumors is likely paralleled by a continuum of tumor-initiating capabilities. In other words, the term “TIC” refers to a quantitative trait that is influenced not only by cancer cell autonomous signaling but also by cellular context (e.g., neighboring malignant cells and the tumor microenvironment). For instance, the tumorigenicity of defined cell populations can depend on parameters such as mouse strain and the use of Matrigel (19, 36). We found a similar effect in that the 5T4hi cells yielded higher tumor incidence when implanted with regular Matrigel as opposed to growth factor-reduced Matrigel. Furthermore we observed 2 examples of context-dependent TIC behavior: the uniformly 5T4hi cells in the PDX-derived culture gave rise to tumors with heterogeneous 5T4 expression (Fig. 3) and the uniformly 5T4hi cells in the tumor-derived culture gave rise to cells with dramatically reduced 5T4 expression under differentiation conditions in vitro (Fig. 4). Xenografts and serum-free cultures can be complementary models to study tumor cell plasticity, hierarchy, and stromal interaction.

Therapeutic targeting of a TIC antigen

5T4 is an oncofetal protein as defined by expression during embryonic development and in cancer but little expression in normal adult tissues. Recent work showed the importance of another oncofetal protein, LICAM, in glioblastoma TICs (37). Unconjugated antibodies directed at TIC surface markers might affect TIC survival, differentiation, and/or interaction with stroma, but many of them are expected to have limited single-agent activity in the clinic. Our data provide preclinical proof of concept for targeting TICs with ADCs. Strikingly, efficacy was observed in KRAS wild-type and KRAS mutant tumors, consistent with the ADC mechanism of action. Future studies could determine whether the anti-5T4 ADC strategy in NSCLC might transcend KRAS status, in contrast to anti-EGFR (epidermal growth factor receptor) therapies (38).

The efficacy of a TIC-directed therapy will likely depend on the proportion and properties of the targeted TICs. Even if quiescent or slow-growing TICs are destroyed or differentiated, tumors with proliferating progenitor-like cells might not regress in the short term (8); on the other hand, immediate therapeutic impact might be achieved if we eliminate proliferating TICs that contribute to both pathologic damage and disease progression. The dramatic, antigen-specific activity of the anti-5T4 ADC might be explained by the proliferative state of 5T4hi TICs, but further studies are needed to fully understand the mechanism, which might also involve a bystander effect (39) and/or drug-induced 5T4 expression (e.g., as observed in 6027A1 PDX following cisplatin treatment; our unpublished data). Because of the continuous nature of 5T4 expression that we observed in some models, we cannot exclude the possibility that the anti-5T4 ADC might target both TICs and non-TICs in some tumors, which would be therapeutically advantageous.

In summary, our study delineates a cellular hierarchy in NSCLC, characterizes the undifferentiated highly tumorigenic cell subpopulation, and shows the application of this knowledge to the development of anticancer therapeutics. Characterization of 5T4 as a TIC marker in NSCLC suggests an explanation for the long-term efficacy of the anti-5T4 ADC despite heterogeneous 5T4 expression in the tumors. Future studies could uncover additional molecules that, even if expressed in only a subpopulation of cells in the tumor, constitute appealing therapeutic targets against aggressive heterogeneous diseases.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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Delineation of a Cellular Hierarchy in Lung Cancer Reveals an Oncofetal Antigen Expressed on Tumor-Initiating Cells

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