Vaccine-Mediated Immunotherapy Directed against a Transcription Factor Driving the Metastatic Process

Andressa Ardiani1, Sofia R. Gameiro1, Claudia Palena1, Duane H. Hamilton1, Anna Kwilas1, Thomas H. King2, Jeffrey Schlom1, and James W. Hodge1

Abstract

Numerous reports have now demonstrated that the epithelial-to-mesenchymal transition (EMT) process is involved in solid tumor progression, metastasis, and drug resistance. Several transcription factors have been implicated as drivers of EMT and metastatic progression, including Twist. Overexpression of Twist has been shown to be associated with poor prognosis and drug resistance for many carcinomas and other tumor types. The role of Twist in experimental cancer metastases has been principally studied in the 4T1 mammary tumor model, where silencing of Twist in vitro has been shown to greatly reduce in vivo metastatic spread. Transcription factors such as Twist are generally believed to be "undruggable" because of their nuclear location and lack of a specific groove for tight binding of a small molecule inhibitor. An alternative approach to drug therapy targeting transcription factors driving the metastatic process is T-cell–mediated immunotherapy. A therapeutic vaccine platform that has been previously characterized consists of heat-killed recombinant Saccharomyces cerevisiae (yeast) capable of expressing tumor-associated antigen protein. We report here the construction and characterization of a recombinant yeast expressing the entire Twist protein, which is capable of inducing both CD8+ and CD4+ Twist-specific T-cell responses in vivo. Vaccination of mice reduced the size of primary transplanted 4T1 tumors and had an even greater antitumor effect on lung metastases of the same mice, which was dependent on Twist-specific CD8+ T cells. These studies provide the rationale for vaccine-induced T-cell–mediated therapy of transcription factors involved in driving the metastatic process. Cancer Res; 74(7); 1945–57. ©2014 AACR.

Introduction

Numerous reports have now demonstrated that the epithelial-to-mesenchymal transition (EMT) process is involved in solid tumor progression, invasion, and metastasis (1–7). Studies have also shown that cells undergoing EMT become more drug resistant (8–13). Several transcription factors have been implicated as drivers of EMT and metastatic progression, including Twist (12), Snail (5), Slug (14), and Brachyury (2, 15), among others; perhaps the most studied of these is Twist. Overexpression of Twist has been shown to be associated with poor prognosis for the following human carcinomas: breast (16, 17), colorectal (18, 19), cervical (20), lung (21), esophageal (22), hypopharyngeal (23), prostate (24), gastric (25), and bladder (26), as well as human melanoma (27), glioblastoma (28), gastrointestinal stromal tumor (29), and osteosarcoma (30). Overexpression of Twist has also been shown to be associated with hormone and drug resistance (17, 21) and the suppression of senescence programs (31).

The role of Twist in cancer metastases has been principally studied in the 4T1 mammary tumor model, where 4T1 cells are transplanted into the mammary fat pad and spontaneously metastasize to the lung. Silencing of Twist in vitro has been shown to greatly reduce in vivo metastatic spread (32, 33). Transcription factors such as Twist are generally believed to be "undruggable" because of their nuclear location and lack of a specific groove for tight binding of a small molecule inhibitor. One study (9) has shown that pretreatment of 4T1 cells in vitro with the antibiotic salminycin before transplant resulted in a 4-fold reduction of metastases, a decrease in the epithelial marker E-cadherin and an increase in the mesenchymal marker vimentin. Pretreatment of 4T1 cells with paclitaxel, however, induced the opposite effects.

An alternative approach to drug therapy to target transcription factors driving the metastatic process is T-cell–mediated immunotherapy. A recent study has shown that T cells from mice vaccinated with a 10-mer Twist peptide could lyse 4T1 tumor cells in vitro (34). This provided evidence that Twist polypeptides could be processed through the cytoplasm and transported in the context of class I major histocompatibility complex (MHC) as a 9–10 peptide–MHC complex on the cell surface for T-cell recognition.
A therapeutic vaccine platform that has been previously characterized consists of heat-killed recombinant Saccharomyces cerevisiae (yeast) capable of expressing tumor-associated antigen (TAA) protein. Recombinant yeast-CEA vaccine was shown (35–39) to efficiently activate murine and human T cells, which are capable of lysing murine and human tumor cells, respectively, and recombinant yeast-CEA vaccination of mice resulted in antitumor activity. These and other studies have shown that yeast (even devoid of the tumor antigen) could efficiently activate murine and human dendritic cells via their Toll-like receptors (TLR) and consequently induce dendritic cells to produce high levels of type I cytokines such as interleukin (IL)-2, TNF-α, and IFN-γ. Thus, the “yeast component” of the recombinant yeast is an integral part of the vaccine platform in its ability to activate the innate immune system and has been shown previously to contribute in part to antitumor effects (35–39).

We report here the construction and characterization of a recombinant yeast expressing the entire Twist protein, which is capable of the induction of both CD8+ and CD4+ Twist-specific T-cell responses in a 4T1 mammary breast cancer model. Vaccination of mice reduced the size of primary transplanted 4T1 murine mammary tumors and had an even greater antitumor effect on lung metastases of the same mice. These antitumor effects were seen in (i) the unrectected setting, (ii) in the neoadjuvant tumor setting where mice were vaccinated before the surgical resection of the primary tumor, and (iii) in the adjuvant setting where primary tumors were surgically removed before the administration of vaccine. These studies provide the rationale for vaccine-induced T-cell-mediated therapy of transcription factors involved in driving the metastatic process.

Materials and Methods

Animals

All mice were housed and maintained in microisolator cages under specific pathogen-free conditions and in accordance with the Association for Assessment and Accreditation of Laboratory Animal Care guidelines. All experimental studies were carried out under approval of the NIH Intramural Animal Care and Use Committee.

Tumor cells

4T1 murine mammary and P815 mouse lymphoblast-like mastocytoma cell lines were purchased from American Type Culture Collection and maintained in the recommended medium.

RNA isolation, quantitative RT-PCR, and EMT array

Tissues were collected from naive mice, and cell lysates were obtained utilizing gentleMACS M Tubes as per the manufacturer’s recommendations (Miltenyi Biotec). Total RNA was isolated from tissue lysates and tumor cell lines using the RNEasy Extraction Kit (Qiagen), and reversed transcribed into cDNA using the Advantage RT-for-PCR Kit (Clontech). cDNA (2.5–10 ng) was used in quantitative real-time PCR reactions using the following probes specific for Twist1 (Mm00442036_m1) and glyceraldehyde-3-phosphate dehydrogenase (GAPDH; 4352339E). Fold change in relative mRNA expression was calculated as expression in 4T1 Twist short hairpin RNA (shRNA) cells relative to control shRNA cells. Relative mRNA expression levels of 84 genes involved in the EMT process were assessed using an EMT PCR array (SA Biosciences) as per the manufacturer’s directions. PCR was performed on the 7300 Real-Time PCR System (Applied Biosystems). Where indicated, values calculated as expression relative to GAPDH as previously described (2).

Immunohistochemistry

Female Balb/c mice (n = 3) were inoculated with 5 × 10^4 4T1 cells on the mammary fat pad on day 0. On day 30, mice were euthanized, primary tumors and lung tissues were harvested. Twist expression was detected via immunohistochemistry using rabbit-polyclonal antibody to Twist (EMD Millipore) according to the manufacturer’s instructions. Expression of mesenchymal markers was detected using rabbit antibody to N-cadherin and vimentin (Abcam). Epithelial marker expression was detected using rabbit antibody to E-cadherin (Cell Signaling). Entire slides were digitally scanned by an Aperio ScanScope CS scanning system and analyzed by Aperio ImageScope Viewer software (Aperio Technologies Inc.). The statistical analysis was composed of three independent murine tumors, within each contained a complete stained tumor section. Positive tumor regions were measured using the Positive Pixel Count v9 algorithm. Negative controls included omission of primary antibody with PBS and matched rabbit isotype antibody.

Generation of Twist knockdowns

4T1 cells were transfected with 1 μg of purified control shRNA or the Twist1-specific targeting shRNA (Origene) using a nucleofector device as per the manufacturer’s recommendations (Lonza). Stable transfectants were selected utilizing puromycin (Sigma-Aldrich).

Western blot analysis

Cells were washed twice with PBS and lysed in RIPA Lysis Buffer (Santa Cruz Biotech). Protein concentration was measured using a BCA Protein Assay Kit (Thermo Scientific). Aliquots containing 40 μg of protein were run on an SDS-PAGE, and transferred to a nitrocellulose membrane. Membranes were blocked for 1 hour at room temperature with 5% milk in PBS and probed overnight at 4°C using antibodies specific for pan-actin (clone Ab-5, NeoMarkers) or Twist (clone 2c1a, Abcam) at the concentrations recommended by the respective manufacturers. Membranes were washed 3 times using PBS containing 0.05% Tween 20 (PBST), and incubated with appropriate IRDye-labeled secondary antibodies (LI-COR Biotechnology) at a 1:5,000 dilution in 5% milk in PBS for 1 hour at room temperature. Membranes were washed 3 times with PBST. All Western blots were imaged using the Odyssey Infrared imaging system (LI-COR Biotechnology).

Proliferation

Five hundred tumor cells were seeded per well in 96-well trays, and cell viability was assessed by MTT. Briefly, MTT
reagent (Sigma-Aldrich) was added per well at a final concentration of 0.5 mg/mL for 2 hours at 37°C. Medium was removed and the converted dye was solubilized in ice-cold isopropanol and measured at 560 nm on a micro plate reader (Bio-TEK Instruments). To evaluate the effect of radiation or chemotherapy on the growth of tumor cells, cells were exposed in vitro to 5 Gy radiation dose or 1 ng/mL docetaxel in complete media or were left untreated. Cells were harvested 24, 48, or 72 hours after exposure, and the total number of adherent viable cells was determined by trypan blue exclusion.

Migration and invasion assays

In vitro cell migratory and invasive abilities were assessed using CytoSelect 96-well cell migration and invasion assays as per the manufacturer’s instructions (Cell Biolabs, Inc.). Briefly, 10^5 tumor cells in serum-free media were seeded into the upper chamber and media containing 20% FBS was placed into the lower chamber. After 24-hour incubation at 37°C, cells that had moved into the lower chamber were lysed and quantified utilizing the CyQuant GR dye solution; fluorescence was measured at 480/520 nm utilizing a micro plate reader (Bio-TEK Instruments). Data are expressed as relative fluorescence units, as per the manufacturer’s instructions.

F-actin staining

Cells were grown on glass coverslips, and stained for F-actin utilizing Alexa Fluor-488 labeled phalloidin (Invitrogen, Life Technologies) as per the manufacturer’s recommendations.

Vaccine constructs

Recombinant *S. cerevisiae* yeast constructs without antigen (wild-type yeast) or expressing the Twist 1 gene protein (referred to here as recombinant yeast-Twist) were engineered by methods similar to those previously described (GlobeImmune; ref. 35). Expression of Twist protein from yeast-Twist was confirmed by Western blot analysis (Supplementary Fig. S1).

Murine CD8+ T-cell responses

Female Balb/c mice (*n* = 5) were vaccinated with PBS, wild-type yeast, or recombinant yeast-Twist vaccine at 1 yeast unit (YU) per site at 4 sites (4 YU total) on days 0, 7, 14, and 21. On day 35, mice were euthanized and spleens were removed, dispersed into single-cell suspensions, pooled, and stimulated for 6 days with 1 μg/mL of Twist peptide (LYQVLQSDEL, CPC Scientific). Bulk lymphocytes were recovered by centrifugation through a Ficoll-Hypaque gradient. For the assay of tumor-killing activity, the recovered lymphocytes and 111In-labeled target cells P815 pulsed with the Twist peptide were incubated for 5 hours and radioactivity in supernatants was measured using a γ counter (Corba Autogamma; Packard Instruments). For IFN-γ production, the pooled splenocytes were stimulated for 7 days with 1 μg/mL of Twist peptide and bulk lymphocytes were recovered by centrifugation through a Ficoll-Hypaque gradient. Recovered T cells were restimulated with fresh, irradiated, naive syngeneic splenocytes (as antigen processing cells, APC) and 1 μg/mL of either Twist peptide or control HIV peptide (AMQMLKETI, CPC Scientific) for 24 hours. Supernatant was collected and analyzed for murine IFN-γ by cytometric bead array (BD Pharmingen) according to the manufacturer’s instructions. Results were background corrected for HIV peptide.

Murine CD4+ T-cell proliferation and flow cytometry

Female Balb/c mice (*n* = 5) were injected with PBS, or vaccinated wild-type yeast or yeast-Twist vaccine at 1 YU per site at 4 sites (4 YU total) weekly for 3 or 4 weeks. Fourteen days after the last vaccination, animals were euthanized and splenocytes were collected and pooled. CD4+ T cells were purified by negative selection using a magnetic separation system (Miltenyi Biotec). To measure Twist-specific proliferation, CD4+ T cells were cocultured with irradiated syngeneic spleen cells (APC) and Twist peptide (QQPASSGKRGARKRRS, CPC Scientific) at 0.4 μg/mL. After 4 days of incubation, 1 μCi of [3H]-thymidine (Perkin-Elmer) was added per well; plates were harvested after 16 hours of incubation and thymidine incorporation was measured using a 1450 Betaplate reader (Perkin-Elmer). To analyze T-cell activation markers, cells were harvested on day 5 and multicolor cytometric analyses for T-cell activation were performed using an LSR-II (BD Biosciences). FoxP3 antibody with appropriate isotype was purchased from eBioscience and the remaining antibodies and their respective isotype control antibodies were purchased from BD Biosciences. Supernatant was also collected and analyzed for IFN-γ by cytometric bead array (BD Biosciences).

Antitumor vaccination

Female Balb/c mice (*n* = 8–10) were injected with 5 × 10^4 4T1 mammary tumor cells. Four days or 11 days after tumor implantation, mice were injected with PBS or with wild-type yeast or yeast-Twist at a dose of 1 YU at 4 sites (4 YU total) and subsequently weekly for the duration of the experiment. Tumor growth was measured twice/week and recorded. Mice were euthanized either on day 21 or when the average tumor volume in each group reached 1,000 mm^3^. To enumerate lung metastasis, lungs were harvested and dispersed into single-cell suspension and plated in the presence of 6-TG (Sigma-Aldrich). Ten days later, cells were fixed with methanol, stained with 0.03% methylene blue, and the number of clonogenic metastatic cells was counted.

Analysis of tumor T-cell infiltration

To determine the presence of T-cell infiltrates in the primary tumors and lung tumor tissues, female Balb/c mice (*n* = 3) were injected with 5 × 10^4 4T1 mammary tumor cells. Four days after tumor implantation, mice were injected weekly with PBS or with wild-type yeast or yeast-Twist at a dose of 1 YU at 4 sites (4 YU total). Mice were euthanized when the average tumor volume in each group reached 1,000 mm^3^. Primary tumors and lungs were harvested and T-cell infiltrates were detected using rabbit-polyclonal antibody to CD3 (Dako) according to the manufacturer’s instructions and analyzed by Aperio ImageScope Viewer software (Aperio Technologies Inc.) as earlier described. Negative controls included omission of primary antibody with PBS and matched rabbit isotype.
T-cell/NK depletion study

Female Balb/c mice \( (n = 8–10) \) were injected with \( 5 \times 10^4 \) 4T1 mammary tumor cells. Four days after tumor implantation, mice were vaccinated weekly with either PBS or wild-type yeast or recombinant yeast-Twist at a dose of 1 YU at 4 sites (4 YU total) and subsequently weekly for the duration of the experiment. On days 4 to 7 and every week thereafter, animals were depleted of CD4\(^+\) T cells, CD8\(^+\) T cells, or both CD4\(^+\) and CD8\(^+\) T cells by intraperitoneal administration of a daily dose (100 \( \mu \)g) of anti-CD4 (GK 1.5) and/or anti-CD8 (Lyt 2.2) hybridomas in PBS. For natural killer (NK) cell depletion, animals were injected with 25 \( \mu \)L anti-asialo-GM1 antibody (Cedarlane) intraperitoneal once per week. Tumor volume was recorded twice/week.

Tumor resection and antitumor vaccination

To model the neoadjuvant tumor setting, female Balb/c mice \( (n = 8–10) \) were injected with \( 5 \times 10^4 \) 4T1 mammary tumor cells. Four days after tumor implantation, mice were vaccinated weekly with either PBS or wild-type yeast or yeast-Twist at a dose of 0.3 YU at 1 site (0.3 YU total). Tumors were allowed to grow and metastasize to distant site. On day 10, primary tumors were removed using sterile technique. To enumerate lung metastasis, mice were euthanized on day 40, lungs were harvested, and the number of clonogenic metastatic cells was counted. To model the adjuvant tumor setting, female Balb/c mice \( (n = 20) \) were injected with \( 5 \times 10^4 \) 4T1 mammary tumor cells. On day 14, primary tumors were surgically removed using aseptic technique and after 1 week, mice were vaccinated with PBS or yeast-Twist at a dose of 1 YU at 4 sites (4 YU total) and weekly thereafter. Mice were observed and their survival was recorded.

Toxicology study

Female Balb/c mice \( (n = 5) \) were vaccinated with either PBS or wild-type yeast or recombinant yeast-Twist at a dose of 1 YU at 4 sites (4 YU total) weekly for 18 weeks. One week following the last injection, animals were assessed for any potential toxicities utilizing the following parameters: in-life body weight, CBC (20 parameters: WBC, LY, MO, EO, RBC, Hb, HCT, MCV, PLT), serum chemistry (5 parameters: BUN, CRE, AST, ALT, ALK), and autoimmunity (5 parameters: Histone, n-RNP, dsDNA, ssDNA, CIC antibodies), as described previously (40).

Statistical analysis

Data were analyzed using GraphPad Prism (Version 5; GraphPad Software). Data points in graphs represent the mean SD.

Results

Expression of Twist in normal tissues and tumors

To evaluate Twist as a potential target of carcinoma therapy, Twist mRNA expression was analyzed in a range of normal murine tissues and the 4T1 tumor cell line (Fig. 1A). High levels
of *Twist* mRNA expression were seen in 4T1 cells and testis, generally considered to be an immunologically privileged site, with lower levels detected in spleen. Some other tissues evaluated showed detectable, albeit low, levels of *Twist* mRNA. Contrary to *Twist*, expression of *Brachyury* mRNA, a different EMT regulator, was negative in all samples evaluated, with the exception of testis (data not shown). The 4T1 line was chosen for further study because of its ability to metastasize spontaneously to the lung, its involvement in EMT demonstrated in previous studies, and the fact that *Twist* was shown to be a mediator of metastatic spread in the 4T1 model (33). Figure 1B shows the significantly higher level of expression of *Twist* in biopsies of 4T1 pulmonary metastases versus primary tumors (*P* = 0.0373; Fig. 1C). Because *Twist* is expressed in some normal organs, the results shown in Fig. 1A also define *Twist* as a "self-antigen" to which Balb/c mice are supposedly immunologically "tolerant."

**Silencing *Twist* expression is associated with a decreased migratory phenotype**

To confirm and extend previous observations that *Twist* is a driver of metastasis in this 4T1 model, it is shown that the reduced level of *Twist* in *Twist* shRNA–transfected 4T1 cells (Fig. 2A) reduced the level of migration (Fig. 2C) and invasion (Fig. 2D). However, *Twist* shRNA-treated cells grow *in vitro* at an identical rate to the control shRNA-treated cells (Fig. 2B). Expression of 84 genes involved in the process of EMT was analyzed by real-time PCR in 4T1 cells stably silenced for the expression of *Twist1* (4T1 Twist shRNA) compared with primary tumors (*P* = 0.0373; Fig. 1C). Because *Twist* is expressed in some normal organs, the results shown in Fig. 1A also define *Twist* as a "self-antigen" to which Balb/c mice are supposedly immunologically "tolerant."

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Silencing *Twist* expression is associated with a decreased migratory/invasive phenotype. The functional role of *Twist* in 4T1 tumor cells was analyzed by gene knockdown. A, Western blot analysis of *Twist* protein in the 4T1 control and *Twist* shRNA cell lines. Actin is shown as the protein loading control. B, proliferation of the 4T1 control and *Twist* shRNA cells was assessed by MTT assay after 1, 3, and 5 days of *in vitro* growth. C and D, *in vitro* cell migration (C) and invasion (D) of the 4T1 cell line pair. Error bars indicate mean ± SEM from triplicate measurements. E, fold change in relative *mRNA* expression in genes known to be involved in the EMT process in 4T1 Twist shRNA relative to control shRNA cells. F, F-actin staining of the 4T1 cell line pair (magnification, ×20). The blue signal represents the DAPI-stained nuclei and the green signal represents the staining of the F-actin.
control cells (control shRNA). Shown in Fig. 2E is the selected group of genes whose expression was either upregulated or downregulated greater than 3-fold in Twist-silenced tumor cells. For example, Mmp-3 and Mmp-9 expression was markedly downregulated; Mmp-3 and Mmp-9 encode for the matrix metalloproteinases-3 and -9, respectively, enzymes known to participate in the breakdown of the extracellular matrix (41). Silencing of Twist1 in 4T1 cells also resulted in a marked (4.3-fold) decrease in the expression of Spp1, the gene encoding for the secreted sialoprotein osteopontin, previously described as a regulator of adhesion, motility, tumor growth, and metastasis (42). The gene most greatly upregulated (50-fold) following silencing Twist in 4T1 cells was Krt14, which encodes for the epithelial marker protein keratin (14). Also markedly upregulated were the genes encoding for fibroblast growth factor binding protein 1 (Fgfbp1) and regulator of G-protein signaling 2 (Rgs2). The former is a protein involved in binding and activation of fibroblast growth factors, whereas regulator of G-protein signaling 2 may inhibit G protein–coupled receptor–mediated signaling via inactivation of G proteins. In addition, silencing Twist expression in 4T1 cells also mediated reorganization of the actin cytoskeleton as indicated by F-actin staining depicted in Fig. 2F. Although tumor cells with high levels of Twist presented F-actin filaments organized into actin stress fibers, silencing of Twist in 4T1 cells promoted cortical organization of F-actin in the areas of cell-to-cell contact. Although Twist was previously implicated in apoptotic evasion (43), in the 4T1 model, however, silencing Twist did not improve cells’ sensitivity to radiation or docetaxel treatment (data not shown). Altogether, our data indicate that Twist plays a functional role in the 4T1 model on the remodeling of the extracellular matrix as well as on the events of tumor cell migration and invasion.

Vaccination with recombinant yeast-Twist induces Twist-specific T-cell responses
To determine whether CD8+ and/or CD4+ Twist-specific immune responses could be elicited in vivo, Balb/c mice were vaccinated 4 times at weekly intervals with recombinant yeast-Twist vaccine, wild-type yeast, or buffer (PBS). Mice were euthanized on day 35. As mentioned above, wild-type yeast have previously been shown to stimulate dendritic cells via TLRs, which, in turn, can activate T cells to produce high levels of type 1 cytokines; the yeast component of the vaccine is thus considered an integral part of the vaccine platform. Splenic T cells from mice in each of the vaccinated groups were pulsed with a 10-mer Twist peptide to activate CD8+ T cells. The splenocytes from mice vaccinated with the recombinant yeast-Twist produced 2-fold more IFN-γ and displayed significantly greater (>3-fold, P = 0.02) lytic activity against 4T1 cells than splenocytes from the wild-type yeast group or no treatment group (Fig. 3A and B). A novel 15-mer Twist peptide was also used to activate CD4+ T cells, and significantly greater proliferative activity and increased IFN-γ production were also seen from splenocytes in the recombinant yeast-Twist vaccinated mice (Fig. 3C and D). These data, taken together, indicate that the recombinant yeast-Twist vaccine can break tolerance to this self-antigen. Analyses of populations of CD4+ memory T cells after in vitro restimulation revealed a 7- and 1.6-fold increase of CD4+ T memory stem cells (Tscm) in Twist-vaccinated mice compared with PBS- or yeast wild-type–treated mice, respectively (Fig. 3E). This recently described Tscm population was thought to generate potent antitumor activity (44).

Antitumor and antimetastatic effect of recombinant yeast-Twist vaccination
Antitumor activity was evaluated in vaccinated tumor-bearing mice. 4T1 cells were transplanted in mammary fat pads on day 0 and mice were vaccinated 3 times at weekly intervals starting on day 4. Mice were euthanized on day 21 and lung metastases were enumerated. As seen in Fig. 4A, on day 21 there was a significant reduction (P = 0.0199) in primary tumor volume in the recombinant yeast-Twist vaccinated group versus the wild-type yeast vaccinated group or PBS vaccinated group (n = 8–10 mice/group). There was also a statistical difference (P = 0.005) in the number of lung metastases in the Twist vaccinated group versus the PBS vaccinated group and a trend but a nonstatistical difference (P = 0.16) between Twist vaccinated and wild-type yeast vaccinated groups (Fig. 4B).

Other studies have shown that immunosuppressive factors, correlating with the size of the primary tumor, can influence the growth of secondary lesions. To control for the possibility that the size of the primary tumor was influencing the number of lung metastases, mice were transplanted with 4T1 in fat pads on day 0 and vaccinated weekly starting at day 4 with recombinant yeast-Twist, wild-type yeast, or buffer; primary tumor volumes were then measured. Mice in each group were euthanized when the average tumor volume reached 1,000 mm3 (Fig. 4C). As seen in Fig. 4D, there was a reduction in the number of lung metastases in the recombinant yeast-Twist vaccinated group versus the wild-type yeast vaccinated group (P = 0.03) and versus the PBS vaccinated group (P = 0.004). Moreover, the percentage of mice with ≤150 clonogenic metastatic cells was 12.5% in the control group, 16% in the wild-type yeast vaccinated group, and 58% in the recombinant yeast-Twist vaccinated group. Analysis of splenic immune populations in tumor-bearing mice receiving no treatment of yeast-Twist vaccine indicated that the yeast-Twist vaccine did not alter the relative percentage or mean expression of Tregs or myeloid-derived suppressor cells (data not shown). Similar observations were attained in non–tumor-bearing mice receiving PBS, yeast wild-type, or yeast-Twist vaccine. Independently of the presence of tumor, yeast-Twist vaccination also did not alter the relative percentage of CD4+ and CD8+ T cells, and NK, B, or dendritic cells and also did not alter the expression of CD28 on both CD4+ and CD8+ T cells (data not shown).

release of cytokines and increase the activation of T cells in the tumor microenvironment. CD8+ T cells are more cytotoxic than CD4+ T cells, and CD4+ T cells can help CD8+ T cells by releasing cytokines.

As seen in Fig. 4A, on day 21 there was a significant reduction (P = 0.0199) in primary tumor volume in the recombinant yeast-Twist vaccinated group versus the wild-type yeast vaccinated group or PBS vaccinated group (n = 8–10 mice/group). There was also a statistical difference (P = 0.005) in the number of lung metastases in the Twist vaccinated group versus the PBS vaccinated group and a trend but a nonstatistical difference (P = 0.16) between Twist vaccinated and wild-type yeast vaccinated groups (Fig. 4B).

Other studies have shown that immunosuppressive factors, correlating with the size of the primary tumor, can influence the growth of secondary lesions. To control for the possibility that the size of the primary tumor was influencing the number of lung metastases, mice were transplanted with 4T1 in fat pads on day 0 and vaccinated weekly starting at day 4 with recombinant yeast-Twist, wild-type yeast, or buffer; primary tumor volumes were then measured. Mice in each group were euthanized when the average tumor volume reached 1,000 mm3 (Fig. 4C). As seen in Fig. 4D, there was a reduction in the number of lung metastases in the recombinant yeast-Twist vaccinated group versus the wild-type yeast vaccinated group (P = 0.03) and versus the PBS vaccinated group (P = 0.004). Moreover, the percentage of mice with ≤150 clonogenic metastatic cells was 12.5% in the control group, 16% in the wild-type yeast vaccinated group, and 58% in the recombinant yeast-Twist vaccinated group. Analysis of splenic immune populations in tumor-bearing mice receiving no treatment of yeast-Twist vaccine indicated that the yeast-Twist vaccine did not alter the relative percentage or mean expression of Tregs or myeloid-derived suppressor cells (data not shown). Similar observations were attained in non–tumor-bearing mice receiving PBS, yeast wild-type, or yeast-Twist vaccine. Independently of the presence of tumor, yeast-Twist vaccination also did not alter the relative percentage of CD4+ and CD8+ T cells, and NK, B, or dendritic cells and also did not alter the expression of CD28 on both CD4+ and CD8+ T cells (data not shown). The primary tumors and lung tumor tissues were subjected to immunohistochemistry staining to detect the presence of CD3+ T-cell infiltrates. The quantification of T-cell infiltrates revealed similar numbers of CD3+ T-cell infiltrates in the primary tumors from mice treated with PBS, wild-type yeast, and yeast-Twist (Fig. 5B). However, an intense staining of CD3+ T-cell infiltrates was detected in lung tumors harvested from mice that received yeast-Twist when compared with other groups (Fig. 5A).
Positive pixel quantification confirmed a significant increase of CD3\(^+\) T-cell infiltrates in lung tumor tissues harvested from mice vaccinated with yeast-Twist versus PBS-treated (\(P = 0.0007\)) and versus wild-type yeast vaccinated group (\(P = 0.0005\); Fig. 5C). Immune depletion studies were conducted to determine which immune cell subset(s) was most responsible for the antitumor effect. As seen in Fig. 5D, CD4 or NK cell depletion had minor effects (nonstatistical) on antitumor activity. Depletion of CD8\(^+\) T cells, however, completely abrogated the antitumor effect of the recombinant yeast-Twist vaccination.

### Antitumor and antimetastatic effect of recombinant yeast-Twist vaccination in the neoadjuvant 4T1 mammary tumor model

The prior studies were conducted with mice vaccinated with 1 YU at 4 sites weekly for 3 weeks, with either recombinant yeast-Twist or wild-type yeast. As was mentioned and shown above, wild-type yeast vaccination was expected to induce some level of antitumor activity. In an attempt to minimize the effect of wild-type yeast vaccination in this model, mice were vaccinated 3 times at weekly intervals with reduced levels of both wild-type yeast and recombinant yeast-Twist: 0.3 YU at a single site (13-fold lower dose than previously used dose of 4 YU). To model the neoadjuvant tumor setting, mice were transplanted with 4T1 tumor cells in the fat pad at day 0, and were vaccinated weekly starting at day 4 throughout the study. On day 14, primary tumors were removed, and mice were euthanized on day 40. As seen in Fig. 6A, there was no statistical difference in tumor volume of mice vaccinated with recombinant yeast-Twist, wild-type yeast, or PBS in the size of primary tumors removed at day 10. Analyses of lungs removed from mice on day 40 (Fig. 6B), however, showed a clear difference in number of lung metastases (\(P = 0.02\)) between mice vaccinated with recombinant yeast-Twist vaccine versus wild-type yeast, and a difference between the PBS vaccinated group and the recombinant yeast-Twist vaccinated group (\(P < 0.0001\)). The percentage of mice with \(\leq1,000\) clonogenic lung metastatic cells was 0% in the control group, 25% in the wild-type yeast vaccinated group, and 71% in the recombinant yeast-Twist vaccinated group. These studies provide evidence...
for a difference in the therapeutic effect of the recombinant yeast-Twist vaccine for metastatic lesions versus the primary tumor lesion, and provide additional evidence that the size of the primary tumor did not affect the ability of the recombinant yeast-Twist vaccine to reduce the number of lung metastases.

**Antitumor and antimetastatic effect of recombinant yeast-Twist vaccination when vaccine administration was delayed and in the adjuvant 4T1 mammary tumor model**

Unlike passive therapies, vaccine induced therapeutic responses require multiple vaccinations at appropriate intervals to maximize immune responses. We have previously shown that multiple vaccinations of recombinant yeast vaccines are required for optimal antitumor responses (39). 4T1 tumors are rapidly growing, and mice bearing unresected 4T1 tumors reach ethical limits for experiments by approximately day 28. If vaccines were initiated on day 14, one could not administer the minimum of three vaccinations required, because mice would be required to be sacrificed at or before the third vaccination. Our data demonstrate that administration of yeast-Twist 4 days after tumor implantation was able to elicit a robust antitumor and antimetastatic effect (Figs. 4 and 6). To further strengthen this finding, we

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**Figure 4.** Antitumor and antimetastatic effect of recombinant yeast-Twist vaccination. In A–D, female Balb/c mice (n = 8–10 per group) were inoculated in the mammary pad with 4T1 mammary tumor cells on day 0. Mice were injected with PBS (open circles) or vaccinated with 1 YU/site at 4 sites of yeast wild-type (squares) or recombinant yeast-Twist vaccine (closed circles). A, mice were vaccinated on days 4, 11, and 18. Primary tumor volume was measured twice a week and recorded. B, on day 21, mice were euthanized and lungs were harvested and dispersed to single-cell suspension and plated. After 10 days incubation, total number of clonogenic metastatic cells was counted. C, mice were vaccinated on day 4 and weekly thereafter. Primary tumor volume was measured twice a week and recorded. When the average of the primary tumor volume for each group reached 1,000 mm³, mice were euthanized, lungs were harvested and dispersed to single-cell suspension, and plated. D, after 10 days incubation, total number of clonogenic metastatic cells was counted. A–D, statistical significance (P < 0.05) between mice that received recombinant yeast-Twist vaccine and mice that received PBS or yeast wild-type. Statistical analyses were done by the Student t test. NS, no significance. This experiment was done two times with similar results. Data shown are representative from one experiment.
performed an additional study in a more rigorous setting where vaccine was given when primary tumor is more established and consequently permitting more tumor cells to metastasize to distant site. Brieﬂy, female Balb/c mice (n = 20 per group) were inoculated with 5 × 10⁴ 4T1 in the mammary fat pad on day 0. Mice were then randomized to receive either PBS or yeast-Twist and the primary tumor volumes were measured. As seen in Fig. 7B, there was a reduction in the number of lung metastases in the recombinant yeast-Twist vaccinated group versus PBS vaccinated group (P = 0.03).

To model the adjuvant setting, we performed additional studies where 4T1 cells were transplanted in mammary fat pads on day 0. On day 11, primary tumors were recorded, the tumors were palpable, and the average tumor volume was 113.4 mm³ (Fig. 7A, inset). Mice were then randomized to receive either PBS or yeast-Twist and the primary tumor volumes were measured. As seen in Fig. 7B, delaying administration of yeast-Twist until day 11 after tumor implantation, where primary tumors are established and thus provide a longer window for tumor cells to metastasize to distant site, still generated a significant primary antitumor effect, albeit less pronounced when compared with earlier vaccine administration. Mice in each group were then euthanized when the average tumor volume reached 1,000 mm³. As seen in Fig. 7B, there was a reduction in the number of lung metastases in the recombinant yeast-Twist vaccinated group versus PBS vaccinated group (P = 0.03).

To model the adjuvant setting, we performed additional studies where 4T1 cells were transplanted in mammary fat pads on day 0. On day 14, primary tumor volume was surgically removed and 1 week later (day 21 after initial tumor implantation), mice were vaccinated with PBS or yeast-Twist vaccine. Survival curve analyses revealed that mice that received yeast-Twist vaccine experienced greater overall survival, presumably by reduced pulmonary metastases burden, compared with mice that received PBS (P = 0.01, not shown).

In light of the fact that Twist is expressed in some normal Balb/c tissues (Fig. 1), it was possible that the antitumor effect of the recombinant yeast-Twist vaccine could also elicit an autoimmune and/or other toxic effects. Balb/c mice
were each vaccinated 18 times at weekly intervals with recombinant yeast-Twist, wild-type yeast, or unvaccinated control. Groups were age matched. Mice were euthanized at 19 weeks. There were no significant differences among any of the groups in (i) body weight, (ii) 20 different blood chemistry parameters, (iii) 7 different clinical chemistry parameters, and (iv) 5 different autoimmunity panels (Supplementary Table S1).

Discussion

The studies reported here show for the first time that a vaccine can induce a therapeutic response targeting a transcription factor that is a driver of the metastatic process. Although both CD4⁺ and CD8⁺ Twist-specific T-cell responses were induced by the recombinant yeast-Twist vaccine (Fig. 3), antibody-mediated depletion studies showed that CD8⁺ T cells were primarily responsible for the antitumor effects (Fig. 5D).
These studies also lend further support to previous studies (2,34,45) that T cells can be generated to transcription factors. Although transcription factors such as Twist and Brachyury are active in the nucleus, these studies provide evidence that transcription factors can be processed in the cytoplasm as polypeptides and transported to the cell surface in the form of 9–10 mer peptide–MHC class I molecule complexes or 15 mer–MHC class II molecule complexes. These peptide–MHC complexes can in turn be recognized by CD8+ and CD4+ T cells, respectively. The studies reported here also demonstrate that Twist is expressed in some normal murine tissues (Fig. 1) and that the vaccine used can break tolerance to the Twist self antigen. More importantly, these studies demonstrate that T-cell–mediated antitumor effects can be induced in the absence of any apparent autoimmunity or other toxic effects (Supplementary Table S1).

It is unclear at this time why the recombinant yeast-Twist vaccine was more effective in the control of the pulmonary metastases versus the primary tumor. One possible explanation is the observation that there is more Twist expression in the metastases than the primary tumor (Fig. 1B–D). This correlates with the significant increase of T-cell infiltrates in the lung tissues from mice treated with yeast-Twist when compared with other treatment groups, whereas similar numbers of T-cell infiltrates were detected in the primary tumors among all groups (Fig. 5A–C). These data suggest that the T-cell infiltrates in the lung tumor tissues are Twist specific. Another explanation is the differences in the tumor microenvironments of the primary versus metastatic lesions.

Although the recombinant yeast-Twist vaccine is shown to be more efficacious in the induction of Twist-specific immune responses and antitumor activity than the wild-type yeast vector (Figs. 3, 4, 6, and 7), the experiments reveal some degree of immune and antitumor effects with the wild-type yeast vector. Previous studies have shown that wild-type yeast can induce a strong innate immune response; treatment of murine or human immature dendritic cells was capable of lysing human tumor cells. A phase I trial is ongoing using a recombinant Brachyury vaccine.

Twist has been shown to be a poor prognostic indicator for a wide range of human tumors (8, 16, 17, 19–22, 25, 29, 46, 47). It is unclear at this time, however, whether it will be a valid target for immunotherapy or other types of therapy because of its fairly high level of expression in several human normal adult tissues (15). It should also be pointed out that although numerous studies with human carcinoma cells have shown a clear correlation between biologic processes of EMT, such as migration, invasion, and phenotypic changes (such as conversion of epithelial markers to mesenchymal markers), this correlation is not as clear with murine carcinoma cell lines. For example, it has been shown (32) that 4T1 cells express E-cadherin but are migratory and invasive, whereas 6NR1 cells express vimentin and N-cadherin, and do not express E-cadherin, but fail to metastasize. In our studies, the expression of Twist corresponds to some, but not all features associated with EMT. In vitro, silencing of Twist expression inhibited the ability of 4T1 cells to migrate and invade, modulated genes associated with EMT and mediated re-organization of the actin cytoskeleton (Fig. 2). In vivo, primary tumors and pulmonary metastases of 4T1 cells were analyzed for 84 genes involved in the EMT process by RT-PCR; several genes that are classically upregulated during the EMT process, such as Cdh2 (N-cadherin), Vim (vimentin), and Zeb2 (Zinc finger E-box binding homeobox 2), were overexpressed in the lung metastasis biopsies by 4.5-, 12-, and 6.2-fold, respectively, when compared with primary tumors. In addition, an EMT array was performed on primary tumors harvested from Twist-vaccinated and nontreated tumors. Tumors from Twist-vaccinated mice demonstrated 3- to 6-fold decrease in expression of genes that are classically upregulated during EMT and the metastasis process, such as N-cadherin (Cdh2), Sox10, Tissue inhibitor of metalloproteinase 1 (Timp1), and Zinc finger E-box binding homeobox 1 (Zeb1, not shown). However, we confirmed that the EMT process in this 4T1 murine model does not exhibit the phenotypic characteristics of EMT in human carcinoma cells. Using immunohistochemistry, we were able to evaluate the expression of classical epithelial marker E-cadherin and mesenchymal markers N-cadherin and vimentin on 4T1 primary tumors and lung metastases (Supplementary Fig. S2). Although there was a significant decrease in E-cadherin expression in lung metastases compared with primary tumors (Supplementary Fig. S2A), comparable N-cadherin and vimentin expression between primary tumors and lung metastases was also observed (Supplementary Fig. S2). This confounding observation further confirmed that the EMT process in murine is not as well defined as in human carcinomas. Another transcription factor, Brachyury, has been shown to be a driver of EMT for a range of human carcinomas. Brachyury has been shown to be differentially expressed in human carcinomas versus normal adult human tissue; it is not expressed in murine carcinomas. Brachyury-specific human T cells have been generated in vitro that are capable of lysing human tumor cells. A phase I trial is ongoing using a recombinant Brachyury vaccine.

The 4T1 model, however, as has previously been shown (32, 33, 41) and reported here, is an excellent model to study the biology of metastatic process. Numerous preclinical studies and several clinical studies have now shown the antitumor synergy between vaccine therapy and chemotherapy, radiation therapy, hormonal therapy, or the use of small molecule targeted therapeutics (48–50). The studies reported here also support the use of the 4T1 model to further study interventions of the metastatic process by using vaccines targeting the transcription factor Twist, as a monotherapy or in a range of combination therapies.
Disclosure of Potential Conflicts of Interest

The Laboratory of Tumor Immunology and Biology, J. Schlom, Chief, has a CRADA with Globimmune. No potential conflicts of interest were disclosed by the authors.

Authors’ Contributions


Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): A. Ardiani, S.R. Gameiro, C. Palena, D.H. Hamilton, A. Kwias, J.W. Hodge

Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): A. Ardiani, S.R. Gameiro, C. Palena, D.H. Hamilton, J. Schlom, J.W. Hodge

Writing, review, and/or revision of the manuscript: A. Ardiani, S.R. Gameiro, C. Palena, D.H. Hamilton, J. Schlom, J.W. Hodge

Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): A. Ardiani

Study supervision: S.R. Gameiro, J. Schlom, J.W. Hodge

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