Targeting Constitutively Activated \( \beta_1 \) Integrins Inhibits Prostate Cancer Metastasis

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Abstract

Disseminated prostate cancer cells must survive in circulation for metastasis to occur. Mechanisms by which these cells survive are not well understood. By immunohistochemistry of human tissues, we found that levels of \( \beta_1 \) integrins and integrin-induced autophosphorylation of FAK (pFAK-Y397) are increased in prostate cancer cells in primary prostate cancer and lymph node metastases, suggesting that \( \beta_1 \) integrin activation occurs in metastatic progression of prostate cancer. A conformation-sensitive antibody, 9EG7, was used to examine \( \beta_1 \) integrin activation. We found that \( \beta_1 \) integrins are constitutively activated in highly metastatic PC3 and PC3-mm2 cells, with less activation in low metastatic LNCaP and C4-2B4 cells. Increased \( \beta_1 \) integrin activation as well as the anoikis resistance in prostate cancer cells correlated with metastatic potential in vivo. Knockdown of \( \beta_1 \) integrin abrogated anoikis resistance in PC3-mm2 cells. In agreement with \( \beta_1 \) integrin activation, PC3-mm2 cells strongly adhered to type I collagen and fibronectin, a process inhibited by the \( \beta_1 \) integrin-neutralizing antibody mAb 33B6. mAb 33B6 also inhibited the phosphorylation of \( \beta_1 \) integrin downstream effectors, focal adhesion kinase (FAK) and AKT, leading to a 3-fold increase in PC3-mm2 apoptosis. Systemic delivery of mAb 33B6 suppressed spontaneous metastasis of PC3-mm2 from the prostate to distant lymph nodes following intraprostatic injection and suppressed metastasis of PC3-mm2 to multiple organs following intracardiac injection. Thus, constitutively activated \( \beta_1 \) integrins play a role in survival of PC3-mm2 cells in circulation and represent a potential target for metastasis prevention.

Visual Overview: [http://mcr.aacrjournals.org/content/11/4/405/F1.large.jpg](http://mcr.aacrjournals.org/content/11/4/405/F1.large.jpg).

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Introduction

Prostate cancer is the second most commonly diagnosed malignancy in men (1). While organ-confined prostate cancer is often successfully treated by surgery, effective treatment for metastatic prostate cancer is lacking. Prostate cancer cells metastasize to multiple sites including bone, lymph node, lung, liver, soft tissues, and the adrenal gland, with lymph nodes and bone being the most common sites (2). For prostate cancer cells to colonize distant organs, cells that dislodge from the prostate need to survive in the circulation before colonizing metastatic sites (3). Although tumors release cancer cells into the circulation frequently (4, 5), the metastatic process is not efficient, as many disseminated cells do not survive in circulation (4, 6). Thus, survival of tumor cells in the circulation is one of the rate-limiting steps in metastasis (7). Understanding the mechanisms that sustain the survival of disseminated prostate cancer cells will be critical for developing strategies for metastasis prevention.

The integrin family of adhesion molecules mediates cell–extracellular matrix (ECM) interactions and signaling, which are essential for normal cell adhesion, migration, and ECM assembly. The integrins consist of 24 glycoprotein heterodimers, composed of combinations of 18 \( \alpha \) and 8 \( \beta \) subunits, which bind to specific subsets of ECM ligands (8). These receptors provide the binding specificity for ECM and transmit signals to promote diverse cellular responses including adhesion, survival, and migration (8). Integrin family proteins have been shown to play a role in the survival of tumor cells (9, 10). Integrins may also mediate interactions between tumor cells and the ECM in the vasculature during the extravasation process, before tumor cells reach their metastatic sites. In prostate cancer cells, \( \alpha_2\beta_1, \alpha_3\beta_1, \alpha_5\beta_1, \alpha_6\beta_1, \alpha_6\beta_3, \alpha_1\beta_3, \) and \( \alpha_4\beta_3 \) integrins are expressed (11). These integrins allow prostate cancer cells...
to interact with multiple ECMs, including type I collagen, laminin and fibronectin (12). Scott and colleagues (13) showed that the binding of PC3 cells to human bone marrow endothelial cells was inhibited by β1 integrin antibody, but not by antibodies to other integrins, suggesting that the attachment of PC3 cells to bone marrow endothelium is primarily mediated by β1 integrins. However, a possible role for integrin activation in the promotion of metastasis had heretofore not been examined.

Integrins are activated by both outside-in and inside-out mechanisms. Outside-in signaling is triggered by integrin binding to its ECM ligand, leading to integrin multimerization and recruitment of signaling and cytoskeletal molecules (14–16). Inside-out signaling occurs when cytoplasmic signals, rather than extracellular ECM ligands, trigger integrin activation (17). Inside-out signaling induces a conformational change of integrins and increases their affinity for ECM ligands (8, 18–20), providing prompt signaling upon encountering ECM proteins. The two mechanisms may be mutually regulatory, as inside-out activation may facilitate outside-in activation and vice versa.

In this study, we showed that constitutive inside-out integrin activation and signaling occur in prostate cells of high metastatic potential and plays a critical role in the survival of prostate cancer cells, thereby enhancing prostate cancer metastasis. We further showed that inhibition of β1 integrin–ECM interaction by an anti-β1 integrin neutralizing antibody significantly reduces the metastasis of prostate cancer cells to lymph nodes and bone.

Materials and Methods

Cell lines and reagents

PC3 and LNCaP cell lines were obtained from American Type Culture Collection. The PC3-mm2 cell line is a highly metastatic cell line derived from PC3 cells through in vivo passages in mice (ref. 21; gift of Dr. Isaiah J. Fidler, MD Anderson Cancer Center). The C4-2B4 is a LNCaP subline (22), kindly provided by Dr. Robert Sikes (University of Delaware, Newark, DE). PC3-mm2, LNCaP, and C4-2B4 cell lines were confirmed by fingerprinting.

The anti-β1 integrin monoclonal antibody mAb 33B6 was generated previously (23). Anti-β1 integrin antibodies mAb MAR4, 9EG7, and 7F10 were purchased from Chemicon, BD Pharmingen, and Novocastra, respectively. Anti-pFAK-Y397 and Alexa Fluor 647 conjugated anti-mouse or anti-rat antibodies were purchased from Invitrogen. Anti-total FAK, AKT, pAKT (Ser473), PARP and cleaved PARP antibodies were purchased from Cell Signaling. Severe combined immunodeficient mice SCID mice were purchased from Jackson Laboratory (Bar Harbor, ME). All experimental procedures involving animals were carried out in compliance with Institutional and governmental requirements and approved by M. D. Anderson's Animal Care and Use Committee.

Flow cytometry for β1 integrin expression

Cells (1 × 10^6) were plated on fibronectin-coated plates for 15 minutes, detached with trypsin, and incubated with β1 integrin antibodies mAB, MAR4 or 9EG7 for 1 hour at 4°C, followed with Alexa Fluor 647-conjugated antimouse or rat antibody for 1 hour, respectively. The fluorescence intensity of the cells was measured by a BD FACSCantoII flow cytometer (BD Biosciences). Cells incubated with mouse or rat normal IgG were used as controls.

FAK and AKT phosphorylation, PARP cleavage, and apoptosis assays

PC3-mm2 cells plated on collagen-coated plate were treated with control IgG or mAb 33B6 for 24 hours. The apoptotic PC3-mm2 cells were detected with sulfobromoducleine 101-Annexin V and DEVD-NUcView 488 caspase-3 substrate using NUcView 488 dual apoptosis assay kit (Biotium). Cell lysates were used in immunoblots with antibodies against total and or cleaved PARP (Cell Signaling), phospho-FAK-Y397-the autophosphorylation site resulting from activated integrins-Cell Signaling), or phospho-AKT (Ser473) and total AKT (Cell Signaling).

Anoikis assay

LNCaP, C4-2B4, PC3, and PC3 mm2 cells were detached by 2 mmol/L EDTA, washed with medium, and resuspended in serum-free medium at 8 × 10^5 cells/mL. Fourteen milliliters of cell suspension was added in a 15 mL conical tube with vent cap, and rotated in an incubator to prevent cell aggregation. For counting live and dead cells, 500 μL of cell suspension was incubated with 2 μmol/L Calcein AM (BD Biosciences) for 30 minutes at 37°C followed by 4 μmol/L propidium iodide (BD Biosciences) for 30 minutes at 37°C. Cells were counted using a fluorescence microscope. To detect apoptotic cells, the cell suspension was centrifuged and washed with PBS, fixed by cold methanol for 30 minutes on ice, and washed again. Cells then were resuspended in PBS with 2 mg/mL Ribonuclease A (Sigma) and 50 μmol/L propidium iodide for 30 minutes on ice, and analyzed by flow cytometry.

β1 integrin knockdown

A β1 integrin viral plasmid (pLKO.1-puro (Sigma) harboring shRNA 5'-GCCCTCCAGATGCAGATAAAA-3') was used to produce lentivirus. A second, non-targeting sequence 5'-GCGCGATAGCGCTAATAATTT-3' cloned in the same vector (Sigma) was used as a control plasmid. To make lentivirus, the viral plasmid was cotransfected with the packaging plasmid pCMV-dR8.2 dvpr and the envelope plasmid pCMV-VSVG (gifts from Dr. Yutong Sun, MD Anderson Cancer Center) into 293FT cells using Lipofectamine 2000 (Invitrogen). Viral supernatant was collected after 48 to 72 hrs and centrifuged at 20,000 rpm for 2 hours to pellet virus particles, which were then resuspended in RPMI medium. PC3-MM2 cells were infected by incubating them with virus particles in the presence of 8 μg/mL of polybrene (Sigma) for 24 hours, and then medium was replaced with 5 μg/mL puromycin for one week to select stable β1 integrin knockdown cells. Cells with decreased β1 integrins have remained stable for 5 passages.
Adhesion assay
PC3-mm2 cells (5 × 10^4 cells/100 μL) prelabeled with 1 μmol/L calcein AM (Invitrogen) were mixed with equal volume of 20 μg/mL mouse IgG, the anti-β1 integrin mAb 33B6, or medium only, and seeded onto 96-well plates that were precoated with 20 μg/mL collagen-I, fibronectin, or bovine serum albumin (BSA). The plates were incubated for 30 minutes at 37°C; the wells were washed with PBS twice, and the cells that adhered to the plate were quantified by measuring the fluorescence intensity at 485/528 nm in each well on a Synergy HT fluorescent plate reader (BioTek).

Parallel plate flow chamber detachment assay
The parallel plate flow detachment assay was conducted as described previously (24). In brief, fibronectin (10 μg/mL) or collagen-I (50 μg/mL in 0.1 M NaHCO₃) was immobilized onto plastic slides. The slides were blocked with 2% BSA before placing into a parallel plate flow chamber. PC3-mm2 cells (2 × 10⁶) treated with or without mAb 33B6 (5 μg/ml) for 5 minutes at 37°C were injected into the flow chamber and allowed to settle on the slide for 10 minutes. A computer-controlled syringe pump (Harvard Apparatus) was used to apply an increasing linear gradient of shear flow to the adhered cells for 300 seconds and the number of cells remaining on the slide was recorded. Shear stress calculations were determined as described (24).

In vitro spreading assay
PC3-mm2 cells (5 × 10⁵) were treated with 20 μg/mL mouse IgG, or 20 μg/mL anti-β1 integrin antibody, or control buffer, seeded onto coverslips coated with collagen-I (20 μg/mL), fibronectin or BSA (20 μg/mL), incubated for 1 hour, and fixed with 4% formaldehyde. Cell morphology was examined under a microscope.

Migration assay
Falcon HTS FluoroBlok inserts were coated with collagen-1, fibronectin or BSA at a density of 5 μg/cm² overnight. Cells (10⁵ cells in 0.3 mL/insert) in serum free RPMI medium containing 20 μg/mL mouse IgG or mAb 33B6 were seeded on the inserts and incubated at 37°C for 24 hours. The migrated cells were labeled with 1 μmol/L calcein AM and counted.

Apoptosis assay
PC3-mm2 cells plated on collagen-coated plate were treated with control IgG or mAb 33B6 for 24 hours. The apoptotic PC3-mm2 cells were detected with sulfonhodamine 101-annexin V and DEVD-νucView 488 caspase-3 substrate using NucView 488 dual apoptosis assay kit (Biotium). Cell lysates were used in immunobLOTS with antibody against cleaved PARP.

Proliferation assay
Cells were mixed with 20 μg/mL mAb 33B6, mouse IgG, or buffer and plated onto the collagen, fibronectin, or BSA-coated plate. Cells were incubated at 37°C for 1 to 4 days. Cell proliferation was determined by viable cell counting.

Intracardiac, intraprostatic injection, and bioluminescence imaging of mice
PC3-mm2 cells were transduced with a retrovirus containing luciferase (Luc) and GFP genes as described previously (25). PC3-mm2-Luc cells were mixed with control IgG or mAb 33B6 at 30 μg/mouse for 30 minutes before injecting into the left ventricle (1 × 10⁶ cells/mouse) or the prostate (0.5 × 10⁶ cells/mouse) of male SCID mice. Mice were injected with control or anti-β1 integrin antibody (30 μg/mouse or 1 mg/kg) before cell inoculation and twice per week thereafter. Tumor growth was monitored weekly using bioluminescence imaging. Images were acquired and analyzed with an IVIS Imaging System (Xenogen).

Immunohistochemical analysis
Formalin-fixed, paraffin-embedded prostate cancer tissue samples from prostate and lymph node metastases obtained from the prostate cancer tissue bank (supported by a SPORE award to The University of Texas M.D. Anderson Cancer Center) were immunostained with mAb 7F10 or anti-pFAKY397 according to the manufacturer’s recommended procedures. The immunostaining was considered positive when more than 10% of the tumor cells were immunoreactive.

Statistical analyses
Two-tailed, paired Student t test was used for statistical analyses. A P value of less than 0.05 was considered statistically significant. Data are expressed as the means ± SD unless otherwise specified. The χ² test was used for immunohistochemical analysis.

Results
β1 integrin expression and activation in human prostate cancer specimens
To assess whether integrin activation occurs in metastatic progression in human prostate cancer, we examined the expression of β1 integrins in human specimens from normal prostate glands, localized prostate cancer, and lymph node metastases. Immunohistochemical analysis showed that in normal prostate glands, β1-integrins are expressed on the basal cell layer and localized at the basal cell/stromal interface, where integrins interact with ECM (Fig. 1A). In prostate cancer specimens, where basal cells are absent, β1 integrins were detected in the membranes in 13 of 20 (65%) primary prostate cancer (Fig. 1A, and Table 1), suggesting that β1 integrins were upregulated in prostate cancer cells. In lymph node metastases, β1 integrins were detected in prostate cancer cells in 13 of 18 (72%) lymph node specimens (Fig. 1A and Table 1). The difference in expression between the normal prostate and primary prostate cancer or lymph node metastasis is significant (P < 0.001 by χ² test). However, there was no correlation between expression of β1 integrins and the Gleason score, and no significant difference in expression of β1 integrins between primary prostate cancer and lymph node metastasis was observed (Table 1).
To examine whether integrin activation occurs in prostate cancer progression, human prostate cancer specimens were examined for the autophosphorylation of FAK at Y397, which results from integrin activation (9). Of the 16 prostate cancer specimens that were evaluated, 7 showed positive staining for pFAK-Y397 (Fig. 1B and Table 2). Of the 12 lymph node metastases, 7 showed positive staining for pFAK-Y397 (Fig. 1B and Table 2). Together, these results suggest that activation of β1 integrins occurs during prostate cancer progression.

β1 integrin activation in prostate cancer cell lines

To examine whether activation of β1 integrins plays a role in prostate cancer metastasis, we determined β1 integrin expression and activation in several available prostate cancer cell lines, including the lymph node–derived LNCaP and its castration-resistant variant C4-2B4, as well as the bone-derived PC3 and its metastatic variant PC3-mm2 cells. LNCaP and C4-2B4 are tumorigenic, however, with low metastatic potential when implanted orthotopically or intracardially. PC3 and PC3-mm2 are tumorigenic and highly metastatic, exhibiting high incidence of metastasis in both spontaneous and experimental metastasis models (25, 26).

Using anti-β1 integrin mAb MAR4, fluorescence-activated cell sorting (FACS) analysis showed that all 4 cell lines expressed high levels of β1 integrins (Fig. 2A). Next, we examined integrin activation in these cell lines. Western blot showed that the levels of phosphorylation of pFAK397 are higher in PC3 and PC3-mm2 than LNCaP and C4-2B4 (Fig. 2B), suggesting that integrin signaling is activated in PC3 and PC3-mm2 cells. We further used the conformation-sensitive antibody 9EG7 (27–29) to examine whether β1 integrins in these cells were present in the activated conformation. 9EG7 bound to PC3 and PC3-mm2 strongly (Fig. 2C). In contrast, 9EG7 showed modest binding to LNCaP and C4-2B4 (Fig. 2C). These observations suggest that β1 integrins are present in an activated conformation only in cell lines with high metastatic potential.

β1 integrin activation correlates with anoikis resistance in prostate cancer cell lines

Next, we examined whether increased β1 integrin activation in prostate cancer cells correlated with cell survival by using an anoikis assay. Single cells from prostate cancer cell

<table>
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<th>Specimens</th>
<th>Total No. Samples</th>
<th>No. of Samples (Gleason Score)</th>
<th>β1 integrins Positive (%)</th>
<th>P Valuea</th>
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<tbody>
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<td>Normal prostate (Luminal cells)</td>
<td>20</td>
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<td></td>
<td></td>
<td>7 (7)</td>
<td>3/5 (60%)</td>
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<td>Primary PCa</td>
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<td>4/7 (57%)</td>
<td>P &lt; 0.001</td>
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<td></td>
<td></td>
<td>6 (9)</td>
<td>2/2 (100%)</td>
<td></td>
</tr>
<tr>
<td>Lymph node metastases</td>
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<td>N/A</td>
<td>13/18 (72%)</td>
<td>P &lt; 0.001</td>
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<tr>
<td></td>
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<td>13/20 (65%)</td>
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Abbreviation: N/A, not applicable.

aFrom chi square tests.
Effects of mAb 33B6 on highly metastatic PC3-mm2 cells.

Silencing of β1 integrins and also the metastatic potential of these cell lines. The decreases in viable cell number corresponded to the increases in dead cell number (Fig. 2D). Analysis of nuclear integrity by propidium iodide staining showed that the increased dead cell number in anoikis conditions correlates with the activation status of β1 integrins in PC3-mm2 cells by expression of shRNA abrogates anoikis resistance. Silencing of integrins and also the metastatic potential of these cell lines. The decreases in viable cell number corresponded to the increases in dead cell number (Fig. 2D). Analysis of nuclear integrity by propidium iodide staining showed that the increased dead cell number in anoikis conditions correlates with the activation status of β1 integrins in PC3-mm2 cells by expression of shRNA abrogates anoikis resistance.

Silencing of β1 integrins in PC3-mm2 cells by expression of shRNA abrogates anoikis resistance.

To examine the causal effect of β1 integrins on prostate cancer cell survival, we used stable expression of shRNA to knockdown β1 integrins in PC3-mm2 cells. As shown in Fig. 3A, transfection of β1 integrin-specific shRNA reduced the expression of β1 integrins by more than 90%, whereas control shRNA did not have significant effects on β1 integrin expression. To examine the effects on integrin-mediated survival pathways, phosphorylation of FAK397 and AKT473 were examined. Knockdown of integrin greatly reduces pFAK397 and pAKT473 phosphorylation (Fig. 3A). Furthermore, the β1 integrin knockdown in suspension are sensitized to anoikis (Fig. 3B), with a concomitant increase in PARP cleavage (Fig. 3C). These results suggest that β1 integrins play a critical role in the survival of highly metastatic PC3-mm2 cells.

Effects of mAb 33B6 on β1 integrin-mediated cell adhesion and migration.

We reasoned that PC3 and PC3-mm2 cells have increased inside-to-outside activation of β1 integrins, leading to increased ECM binding affinity, which increases the adhesion, migration, and survival of the tumor cells during extravasation. Thus, we examined the effects of mAb 33B6, a β1 integrin-neutralizing antibody, on ECM-mediated adhesion, migration, and apoptosis of PC3-mm2 cells. In a static binding assay, PC3-mm2 adhered to type I collagen or fibronectin-coated dishes efficiently compared with noncoated or BSA-coated plates (Fig. 4A) and the adhesion was inhibited by mAb 33B6 but not by control IgG (Fig. 4A). The β1 integrin-mediated adhesion was further examined under flow conditions using the parallel plate flow detachment assay that mimics tumor cells in circulation. mAb 33B6 led to the detachment of PC3-mm2 cells from collagen or fibronectin-coated surface when compared to control IgG (Fig. 4B). When plated on type I collagen or fibronectin-coated plates, PC3-mm2 cells showed a flattened morphology with lamellipodia-like projections, but remained rounded when plated on BSA-coated plates (Fig. 4C). The cell spreading on collagen or fibronectin-coated plates was inhibited by mAb 33B6 (Fig. 4C).

We further examined the effect of mAb 33B6 on the migration of PC3-mm2 cells. Little migration of PC3-mm2 cells was observed on the control BSA-coated wells, but the migratory activity was significantly stimulated by type I collagen or fibronectin (Fig. 4D). The ECM-induced PC3-mm2 migration was significantly inhibited by mAb 33B6 but not by control IgG (P < 0.05). In addition, treatment of PC3-mm2 cells with mAb 33B6 led to the inhibition of FAK and AKT phosphorylation (Fig. 4E). This treatment led to an approximate 3-fold increase in Annexin V staining and caspase-3 activation compared with IgG-treated control cells (Fig. 4F). Western blotting showed a 2- to 3-fold increase in PARP cleavage upon treatment with mAb 33B6 (Fig. 4F), suggesting that blocking PC3-mm2 interaction with ECM resulted in an increase in PC3-mm2 cell apoptosis. Because mAb 33B6 induced approximately 3% apoptosis in PC3-mm2 cells (Fig. 4F) and reduced migration of these cells to approximately 10% to 20% relative to that of untreated control cells, the effects of mAb 33B6 on PC3-mm2 cell migration are not due to its effect on cell viability. However, ECM inhibition did not affect the proliferation of PC3-mm2 cells on type I collagen, fibronectin, or BSA-coated plates (data not shown). mAb 33B6 also did not have
Figure 2. β1 integrin activation correlates with anoikis resistance in PCa cell lines. A, FACS using anti-total β1-integrin antibody mAb MAR4. LNCaP, C4-2B4, PC3, and PC3-mm2 cells showed similar levels of binding with mAb MAR4. B, Western blot analysis of cell lysates for the expression of FAK and phosphorylated FAK Y397. FAK is phosphorylated at Y397 in PC3 and PC3-mm2 cells, but not LNCaP or C4-2B4 cells. C, FACS using conformation sensitive anti-β1-integrin antibody mAb 9EG7. High percentage of PC3 and PC3-mm2 showed specific binding with the conformation-sensitive mAb 9EG7, whereas LNCaP and C4-2B4 showed modest binding. D, cells were grown in anoikis condition as described in Materials and Methods. Viable and dead cell numbers were determined by Trypan Blue exclusion and propidium iodide staining, respectively. PC3 and PC3-mm2 are more resistant to anoikis-induced cell death than LNCaP and C4-2B4 cells. E, FACS of propidium iodide-labeled cells after the cells were grown in anoikis conditions for 24 or 48 hours. LNCaP and C4-2B4 have higher sub-G1 fraction than PC3 or PC3-mm2 cells. F, Western blot analysis of PARP and cleaved PARP of PC3 or PC3-mm2 grown under anoikis conditions for various lengths of times.
Inhibition of PC3-mm2/ECM interaction decreases lymph node metastasis in vivo

Next, we examined the role of prostate cancer/ECM interaction in the ability of prostate cancer cells to metastasize to lymph nodes. Dislodged prostate cancer cells that survive in the circulation usually metastasize first to lymph nodes adjacent to the prostate, then to distant lymph nodes (30, 31). We used the intraprostatic injection model that mimics spontaneous metastasis in vivo and examined whether inhibition of PC3-mm2/ECM interaction would block the metastasis of PC3-mm2 cells from the prostate to the lymph node. Luciferase-labeled PC3-mm2 cells were implanted intraprostatically into SCID mice and the mice were treated with or without mAb 33B6 twice per week. Tumor growth in the prostate and its metastases in the lymph nodes were monitored using bioluminescence. At 2 weeks postinjection, we observed that PC3-mm2 had metastasized from the prostate to multiple lymph nodes in the control IgG-injected mice (Fig. 5A). In contrast, no obvious metastases in distant lymph nodes were detected in mice treated with mAb 33B6 (Fig. 5A). At 3 weeks postinjection, mice were killed and tumors were harvested from the primary (prostate) and metastatic (lymph nodes) sites. In the control IgG-treated mice, PC3-mm2 cells metastasized to both regional and distant lymph nodes, based on bioluminescence imaging and postmortem tissue harvesting (Fig. 5A). In the mAb 33B6-treated mice, PC3-mm2 cells mainly metastasized to regional lymph nodes (Fig. 5A). Upon postmortem dissection, the presence of tumor cells in the lymph nodes was further confirmed by histology. The incidence of lymph node metastasis from intraprostatic injection of PC3-mm2 cells was 100%. An average of 7.2 ± 2.6 lymph node metastases versus 2.3 ± 1.8 (P < 0.001) was detected in the IgG-treated and mAb 33B6-treated mice, respectively (Fig. 5B). The decreases in tumor metastases to distant lymph nodes in mAb 33B6-treated group are not due to tumor size as one of the mice in mAb 33B6-treated group produced a large tumor but exhibited metastasis only to the local lumbar lymph node (data not shown). In addition, the average tumor sizes were similar between the control and mAb 33B6-treated groups (Fig. 5C). These results indicate that inhibition of interaction of PC3-mm2 cells with the ECM limits the ability of tumor cells to metastasize to distant lymph nodes.

Inhibition of PC3-mm2/ECM interaction on disseminated PC3-mm2 cells in vivo

Next, we examined whether blocking PC3-mm2/ECM interaction by mAb 33B6 affects the metastatic growth of disseminated PC3-mm2 cells. We mimicked the hematogenous dissemination of cancer cells by injecting luciferase-
labeled PC3-mm2 cells intracardially. Bioluminescence imaging was used to examine the metastases of PC3-mm2 in vivo. PC3-mm2 cells were considered disseminated into the circulation if bioluminescence signals were detected throughout the whole body (Fig. 6A). Bioluminescence signals subsided one day postinjection (data not shown) and the signals started...
to appear at multiple organ sites at 7 days postinjection (Fig. 6A). Tumor volumes in the control IgG-treated group exhibited an exponential growth at multiple organ sites at 2 and 3 weeks postinjection (Fig. 6A). In contrast, the growth of tumors in the mAb 33B6-treated mice was significantly decreased (Fig. 6A). Quantification of the tumor sizes based on bioluminescence intensity showed no significant difference in tumor volume between the control and mAb 33B6-treated mice at 7 days after tumor injection; however, the average tumor size was significantly smaller at 14 days, with mAb 33B6-treated tumor burden only 7% of that in the control group (P < 0.003). At 20 days, the average tumor burden of anti-β1 integrin-treated mice was 6% of those of control mice (P < 5 × 10⁻⁶; Fig. 6B). We also examined the tumor burden in femurs/tibias and found that the tumor sizes were also significantly reduced in the mice treated with mAb 33B6 (Fig. 6C). These in vivo data are consistent with the in vitro data, which together indicate that activation of β1-integrins increases tumor cell survival and extravasation, resulting in increased tumor metastasis to distant metastatic sites.

**Discussion**

Our studies suggest that constitutive activation of β1 integrins plays a critical role in prostate cancer metastasis. Metastasis is a multistep process and failure to complete any one of these steps will prevent tumor cell colonization at distant sites (4, 32). Two of the key steps for prostate cancer cells to successfully metastasize are survival in the circulation and extravasation of the cells from the circulation into the bone microenvironment. Our results suggest that constitutively activated integrins in prostate cancer cells contribute to their metastatic potential by increasing their resistance to anoikis-induced cell death during tumor dissemination and enhancing their interactions with ECM during extravasation.

A model that summarizes the *in vitro* and *in vivo* results is shown in Fig. 6D. We suggest that in highly metastatic prostate cancer cells, β1 integrins are present in an activated conformation through an inside-out activation mechanism, which increases its ligand-binding affinity. Upon binding with ECM, β1 integrins are further activated by an outside-in mechanism that results in integrin clustering and activation of a downstream signaling cascade that enhances the metastatic potential of prostate cancer cells (Fig. 6D). Our *in vitro* and *in vivo* findings are further corroborated with the observations that in human prostate specimens, where not only was β1 integrin expression upregulated, but its downstream signaling molecule FAK was also activated (pFAK397) in prostate tumors and lymph node metastases, suggesting that this mechanism is clinically relevant. Our studies thus identify constitutive activation of β1 integrins as one of the critical mechanisms in the metastatic progression of prostate cancer and suggest that specifically targeting activated β1 integrins or integrin signaling may inhibit prostate cancer metastasis.

**β1 integrin isoforms**

β1 integrins contain several alternatively spliced variants. For the human β1 subunit, at least 5 different cytoplasmic variants, that is, β1A, β1B, β1C, β1C-2, β1D have been identified (33). Among the 5 known β1 integrin cytoplasmic variants, β1A and β1C have been shown to differentially affect prostate cell functions (34). The β1A variant was shown to act as a stimulator of cell proliferation, whereas the β1C variant acted as an inhibitor of proliferation. Goel and colleagues (35) further showed that β1C expression increases the levels of an extracellular matrix protein thrombospondin 1, which inhibits angiogenesis. While β1A protein is ubiquitously expressed, β1C protein levels are reduced in neoplastic prostate epithelium (34). Prostate cancer cell...
lines, including PC3, LNCaP and DU145, mainly express \( \beta_1 \alpha \) integrins (35). Thus, the \( \beta_1 \) integrins activated in PC3-mm2 cells are the \( \beta_1 \alpha \) variants.

**Inside-out integrin activation**

The mechanism(s) by which \( \beta_1 \) integrins are activated in PC3 and PC3-mm2 cells are not known. Integrins are

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Figure 6. Inhibition of disseminated PC3-mm2 cell growth in vivo by mAb 33B6. Luciferase-labeled PC3-mm2 cells (1 \( \times \) 10^7) were injected into the left ventricle of SCID mice. Mice were treated with IgG or mAb 33B6 (1 mg/kg) before tumor cells inoculation and twice a week subsequently by intraperitoneal injection. A, bioluminescence imaging of mice was conducted within 30 minutes of injection and weekly afterwards to monitor tumor growth in vivo. B, overall tumor burden was recorded as photons per second. Average photon numbers \( \pm \) SE of the control and mAb 33B6-treated mice are presented. C, tumor burden in the femurs of the control and mAb 33B6-treated mice.

\( * \), \( P < 0.05 \). D, model of activated \( \beta_1 \) integrins enhancing prostate cancer metastasis. In highly metastatic prostate cancer cells, \( \beta_1 \) integrins are present in an activated conformation through an inside-out activation mechanism, which increases its ligand-binding affinity. Upon binding with ECM, \( \beta_1 \) integrins are further activated by an outside-in mechanism that results in integrin clustering and activation of a downstream signaling cascade that enhances the metastatic potential of PCa cells.
normally expressed in an inactive state and can be activated through inside-out or outside-in mechanisms. While the ECM ligand-induced outside-in integrin activation increases the avidity (36, 37), inside-out integrin activation increases its ligand binding affinity, cell adhesion, migration, and ECM assembly (8, 18–20). The activation of \( \beta_1 \) integrins in PC3-mm2 cells is likely through an inside-out mechanism, which induces conformational changes of \( \beta_1 \) integrins in the absence of ECM ligands (17). Diverse mechanisms have been shown to contribute to the inside-out activation, which include interaction of the integrin cytoplasmic domain with its regulatory molecules (20, 38), biochemical modification of the integrin molecule, and regulation by extracellular growth factors (39). Talin binding to the cytoplasmic domain of integrins is one of the mechanisms that leads to inside-out integrin activation (20, 38). Sakamoto and colleagues (40) showed that talin1 overexpression increased prostate cancer cell adhesion, migration, and resistance to anoikis, and talin1 levels were higher in metastatic tissue compared with primary prostate tumors. Talin1 overexpression was also observed in aggressive oral squamous cell carcinomas (41). These observations suggest that increase in talin1 levels may play a role in the inside-out activation of \( \beta_1 \) integrins in PC3-mm2 cells. However, we did not detect differences in talin1 expression among C4-2B4 and PC3-mm2 cells by Western blot analysis (data not shown). Extracellular growth factors have been shown to activate integrins (39). In breast cancer cells, Chandrasekaran and colleagues (42) showed that insulin-like growth factor-1 and CD98 regulate \( \alpha_\text{c} \beta_1 \) integrin activation. Interestingly, Chatterjee and colleagues (43) showed that the chemokine CCL2 increased \( \beta_1 \)-integrin activation in PC3 cells. Both IGF-1 and CCL2 have been shown to be upregulated during prostate cancer progression (44, 45), suggesting that these or other growth factors may regulate activation of \( \beta_1 \) integrins in PC3-mm2 cells. Delineating the mechanisms that lead to inside-out activation of \( \beta_1 \) integrins in PC3-mm2 cells may provide additional strategies for metastasis prevention. Further study on the mechanisms of integrin activation and mechanisms by which \( \beta_1 \) integrins become constitutively activated in highly metastatic prostate cancer cells are warranted.

**Targeting activated \( \beta_1 \)-integrins as antimetastatic therapy**

While our study and several other studies showed that blocking integrin/ECM interactions is effective in inhibiting tumor growth (35, 46, 47) or metastasis (11, 48) in mouse tumor models, ECM proteins are also involved in many cellular activities essential for normal cell functions, raising the possibility of high toxicity with anti-integrin therapy. However, our studies showed that \( \beta_1 \) integrins are activated in highly metastatic but not in low metastatic prostate cancer cells or normal prostate epithelial cells. Thus, an anti-\( \beta_1 \) antibody that specifically inhibits the “activated conformation” of \( \beta_1 \) integrins may increase target specificity in selectively targeting only activated integrins. Consistent with such an idea, a monoclonal antibody that targets a tumor-specific, conformationally exposed epitope of wild-type EGFR (mAb 806) has recently been developed for the purpose of reducing the side-effect from anti-EGFR treatments (49). Whether it is possible to generate such a conformation-specific antibody for therapeutic application remains to be seen. On the other hand, an antibody against \( \alpha_\text{c} \) integrin (DI17E6) is being tested in a clinical trial for the treatment of progressive castrate-resistant prostate cancer with bone metastasis (50). \( \alpha_\text{c} \) integrin is expressed in a number of human cancers, including prostate cancer (11), as well as cells in the tumor environment, for example, osteoclasts, osteoblasts, and angiogenic blood vessels. A preliminary report suggests that DI17E6 was well tolerated (50). Completion of this study will reveal whether blocking tumor cell/ECM interaction is feasible for cancer treatments. Because metastasis is the major cause of cancer mortality, there is a strong interest in developing “antimetastatic” therapies, especially in prostate cancer, as the disease is often caught early and there is nearly a 10-year “window” during which antimetastatic therapy would be useful as “secondary prevention.” In addition to anti-integrin antibodies, several “anti-metastatic” therapies are also being developed, including the use of anti N-cadherin (51), anti-cadherin 11 (25) antibodies.

**Prostate cancer cell/ECM interactions at distant metastatic sites**

Besides occurring in circulation, prostate cancer/ECM interactions have been shown to be involved in the progression of cancer in their metastatic sites (4, 52, 53). Type I collagen is the most abundant ECM in bone, raising the possibility that \( \beta_1 \) integrins may play a role in metastatic progression of prostate cancer in bone. Indeed, Kostenuik and colleagues (54) showed that bone cell matrix promotes the adhesion of human PC3 cells via \( \alpha_\text{c} \beta_1 \) integrins. Hall and colleagues (55) showed that LNCaP cells selected for binding to collagen exhibited increased levels of the \( \alpha_\text{c} \beta_1 \) integrins and increased tumorigenesis in bone when the cells were injected into mouse tibia. In this study, we found that mAb 33B6 reduced tumor volume in bone when PC3-mm2 cells were injected intracardially. Whether mAb 33B6 also inhibits PC3-mm2 cell/bone matrix interaction requires further investigation.

Metastatic progression of prostate cancer significantly impacts the survival of men with prostate cancer. Thus, there is an urgent need to identify strategies for the prevention or treatment of metastasis. \( \beta_1 \) integrin antibody has been previously shown to inhibit breast (46) or prostate (35) tumor growth at subcutaneous sites. Our studies provide new evidence that constitutively activated \( \beta_1 \) integrins play a role in the metastasis process and our preclinical studies suggest that strategies that inhibit activation of \( \beta_1 \) integrins may be developed for preventing prostate cancer metastasis.

**Disclosure of Potential Conflicts of Interest**

No potential conflicts of interest were disclosed.
Authors' Contributions

Conception and design: Y.-C. Lee, J.-K. Jin, B.W. McIntyre, C.J. Logothetis, G.E. Gallick, S.-H. Lin
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Targeting Constitutively Activated β1 Integrins Inhibits Prostate Cancer Metastasis
