Macrophage-Dependent Cleavage of the Laminin Receptor \(\alpha 6\beta 1\) in Prostate Cancer

Isis C. Sroka\(^1\), Cynthia P. Sandoval\(^3\), Harsharon Chopra\(^3\), Jaime M. C. Gard\(^3\), Sangita C. Pawar\(^1\,\(^3\), and Anne E. Cress\(^2\,\(^3\)

Abstract

The laminin-binding integrin \(\alpha 6\beta 1\) plays a major role in determining the aggressive phenotype of tumor cells during metastasis. Our previous work has shown that cleavage of the \(\alpha 6\beta 1\) integrin to produce the structural variant \(\alpha 6\beta 1\) on tumor cell surfaces is mediated by the serine protease urokinase plasminogen activator (uPA). Cleavage of \(\alpha 6\beta 1\) increases tumor cell motility, invasion, and prostate cancer metastasis, and blockade of uPA inhibits \(\alpha 6\beta 1\) production. In human tumors, uPA and uPAR are expressed in tumor cells and tumor-associated macrophages (TAM). TAMs localize to solid tumors and contribute to increased tumor growth and the metastatic phenotype. In this study, we utilized a coculture system of PC-3 prostate tumor cells and macrophages [12-O-tetradecanoylphorbol-1-3-acetate (TPA)-differentiated human leukemia HL-60 cells] to investigate the hypothesis that macrophages stimulate the production of the prometastatic variant \(\alpha 6\beta 1\) on human prostate cancer cells via the uPA/uPAR axis. Our results indicate that adherent macrophages cocultured with PC-3 cells increased PC-3 uPAR mRNA, uPAR cell surface protein expression and \(\alpha 6\) integrin cleavage. The stimulation does not require macrophage/tumor cell contact because macrophage conditioned medium is sufficient for increased uPAR transcription and \(\alpha 6\) cleavage-dependent PC-3 cell invasion. The increased cleavage was dependent on uPAR because production was blocked by silencing RNA–targeting uPAR. These results indicate that macrophages can stimulate uPA/uPAR production in tumor cells which results in \(\alpha 6\) integrin cleavage. These data suggest that TAMs promote prometastatic integrin-dependent pericellular proteolysis. Mol Cancer Res; 9(10); 1319–28 ©2011 AACR.

Introduction

Chronic inflammation is a major contributor to tumor initiation, progression, and metastasis in multiple cancer types, including prostate cancer (1, 2). The main determinant of patient mortality is the aggressive phenotype of cancer cells, which is dictated by their capacity to invade and metastasize (3). Inflammatory responses in the solid tumor environment promote tumor metastasis by recruiting migratory immune cells such as macrophages, which originate from blood monocytes in the bone marrow. These tumor-associated macrophages (TAM) are attracted from circulation to the tumor due to neoplastic production of inflammatory cytokines and chemokines and will undergo differentiation at the tumor site (4). Therefore, these specific macrophages are considered to be a tumor educated and tumor-specific macrophage (5, 6). The TAMs can produce various growth factors and cytokines which increase the survival and metastatic capabilities of tumor cells (7) and also directly affect the degradation of the basement membrane surrounding tumor cells by secreting proteases (8, 9).

The presence of TAMs is correlated with poor patient outcome in aggressive tumors including breast, cervical, and bladder cancer (10). The density, size, and location of tumor-infiltrating macrophages in prostate cancer were reported as powerful predictors of patient outcome (11) and prostate cancer specimens harbor increased positive cells expressing the macrophage-specific marker CD68 compared with benign glands (12). More recently, it was shown that expression of macrophage colony-stimulating factor (M-CSF) and its receptor CSF-1 receptor (CSF-1R) are increased in primary tumors of patients exhibiting metastatic disease (13), although other studies have shown variable evidence for TAMs during prostate cancer progression (11, 12, 14, 15).

The metastatic process during prostate cancer progression is accompanied by significant alterations in the composition of the basement membrane and interactions between extracellular matrix proteins and cell surface receptors called...
integrins. TAMs can affect these interactions dramatically as reviewed by Coussens and colleagues (1). Integrins are type 1 transmembrane receptors which bind extracellular matrix proteins including collagens, laminins, fibronectin, and vitronectin. In humans, there are currently 18 alpha and 8 beta subunits which form 24 noncovalently associated and unique alpha and beta heterodimers (16). Previously, we identified that human prostate cancer expresses exclusively laminin receptors (α3β1, α6β1, and α6β6; ref. 17). Prostate cancer cell migration and bone metastasis in vivo (18, 19) depends upon the production of a variant form of α6β1 created by removal of the extracellular binding domain via the serine protease urokinase plasminogen activator (uPA). uPA is a serine protease which converts plasminogen to plasmin by binding with high affinity to either the membrane-bound or soluble uPAR. The uPA system plays a significant role in promoting cancer invasion and metastasis through regulation of pericellular proteolysis. Recent evidence has shown that uPAR signaling to promote tumor progression is also coordinated by interactions with the integrin family of receptors (20). Studies have determined that uPAR is expressed in multiple tumor-associated cell types, including the tumor cells and tumor-associated stromal cells, neutrophils, and macrophages (21, 22). In prostate cancer, the uPA/uPAR system is associated with prostate cancer metastasis (23, 24). Recent work by Zhang and colleagues shows the requirement for stromal uPA and uPAR in promoting prostate tumor growth and macrophage infiltration in vivo (25).

The goal for this study was to determine whether macrophages induced cleavage of the α6 integrin to the variant α6β6 through activation of the uPA/uPAR system in prostate tumor cells. To carry out these studies, we used a coculture system comprised of prostate tumor cells and the human myeloid leukemia HL-60 cell line treated with the phorbol ester 12-O-tetradecanoylphorbol-13-acetate (TPA) as a model for macrophages. Results presented here show that macrophages cocultured with PC-3 cells induced uPAR expression and cleavage of the α6 integrin receptor on the prostate tumor cell lines. Macrophage stimulation of integrin cleavage and uPAR expression was not reliant on direct contact between the macrophages and tumor cells because macrophage conditioned medium induced uPAR expression and α6 cleavage on PC-3 cells and α6 cleavage on the DU-145 cell line. Increased PC-3 invasion in response to macrophage conditioned media and human primary monocytes was inhibited by an α6 cleavage-blocking antibody. Small interfering RNA (siRNA) targeting uPAR abrogated macrophage-induced integrin cleavage, indicating the requirement for uPAR in regulating macrophage-mediated cleavage of the receptor.

Materials and Methods

Antibodies and reagents
The antibody recognizing uPAR used for flow cytometry was a mouse monoclonal (Clone 3/B10, 3936) from American Diagnostica. The mouse monoclonal antibody against the c-terminus of uPAR (MAB807) used for immunoblot analysis was from R&D Systems. The J1B5 rat monoclonal used for immunoprecipitation and flow cytometry analysis which recognizes α6 was generated by Dr. Caroline H. Damsky. The AA6A rabbit polyclonal recognizing the c-terminus of α6 used for immunoblot has been previously characterized by our group and was generated and purified by Bethyl Laboratories. The J8H antibody against α6 has been previously described (19). The CD13 and CD68 phycoerythrin (PE)- and fluorescein isothiocyanate–conjugated antibodies for flow cytometry were obtained from BioLegend. The actin polyclonal antibody used for immunoblot was from Cytokeleton and the tubulin antibody was from EMD Bioscience. The horseradish peroxidase (HRP)–conjugated secondary antibodies used for immunoblotting were from Jackson Immunoresearch Laboratories, Inc. TPA was obtained from Ted Pella, Inc. Carboxyfluorescein diacetate, succinimidyl ester (CFSE) Cell Tracer Proliferation Kit was obtained from Invitrogen. Matrigel was obtained from BD Bioscience.

Cell culture and coculture conditions
Human prostate cancer PC-3 and DU-145 cells and myeloid leukemia HL-60 cells were obtained from American Type Tissue Collection and maintained in Iscove's modified Dulbecco's medium (IMDM; Invitrogen) supplemented with 10% FBS (Hyclone Laboratories). The cells were grown at 37°C in a 5% CO2 atmosphere with constant humidity. Coculture experiments using the prostate tumor cells and TPA-differentiated HL-60 cells were conducted according to the flow chart given in Figure 1A. The HL-60 cells (1 × 10⁶ cells) were treated with 32 nmol/L TPA in IMDM medium for 72 hours to induce differentiation of HL-60 cells into adherent macrophages. After 72 hours, the medium was aspirated and the cells were rinsed with PBS. IMDM supplemented with 10% FBS was added without TPA. Prostate cells were labeled with CFSE (10 μmol/L) according to manufacturer recommendations (Invitrogen). The CFSE-labeled prostate cells were incubated with the adherent macrophages for 24, 48, or 72 hours. At each time point the cocultures were harvested using 5 mmol/L EDTA/PBS, and the CFSE expressing prostate cells were isolated from the macrophages using a FACSAria cell sorter (BD Bioscience). Macrophage conditioned medium was collected from TPA-differentiated HL-60 cells incubated for 24, 48, or 72 hours in IMDM medium supplemented with 10% FBS.

Isolation of human monocytes
Human monocytes were isolated from normal donor peripheral blood by mononuclear cell adherence to plastic culture dishes as previously described (26). Briefly, peripheral blood from a normal donor was diluted 1:1 in RPMI and mixed by gentle inversion. Ficoll was layered on top of the diluted blood in an equal volume. The samples were centrifuged at 400 × g for 40 minutes with slow deceleration at room temperature. The top layer was aspirated and the peripheral blood leukocytes were isolated from the buffy
layer and washed with PBS and centrifuged for 3 minutes at room temperature. The cells were cultured in Dulbecco’s modified Eagle’s medium (DMEM; Invitrogen) supplemented with 1-glutamine (2 mmol/L), 10% FBS, and penicillin/streptomycin for conditioned medium experiments. Isolated cells were fixed with Fix and Perm reagent according to manufacturer’s recommendations (Invitrogen) and flow cytometry for CD68 expression was used to identify monocytes.

**Flow cytometry analysis**

Flow cytometry analysis was used to determine uPAR cell surface expression on PC-3 cells cultured with macrophages. PC-3 cells previously labeled with CFSE were cultured with macrophages for 24, 48, or 72 hours, as outlined in the Culturing Methods section. The cells were harvested using 5 mmol/L EDTA/PBS and 1.5 × 10^6 cells were used per experimental condition. The cells were washed in 0.2% bovine serum albumin (BSA)/PBS and centrifuged at 1,000 rpm at 4°C for 2 minutes. The cells were suspended in 500 μL 0.2% BSA/PBS with a uPAR-specific antibody (American Diagnostica) diluted 1:200. Antibody binding was detected using goat anti-mouse IgG PE conjugated antibody diluted 1:500 (Invitrogen). All antibody reactions were incubated on ice for 30 minutes with gentle vortexing every 5 minutes. Flow cytometry experiments to determine uPAR levels on differentiated HL-60 cells used Alexa Fluor 488 (Invitrogen) secondary antibody diluted 1:500 for antibody-binding detection. Flow cytometry experiments to determine CD68^- human monocytes required an anti-CD68–PE antibody diluted 1:100 for detection. DU-145 and differentiated HL-60 cultures were analyzed by flow cytometry using an anti-CD13–PE antibody diluted 1:100 for detection.

**Immunoprecipitation and immunoblot analysis**

The α6 integrin was immunoprecipitated (IP) from PC-3 and DU-145 cells using the J1B5 antibody (1:100) in radioimmunoprecipitation assay (RIPA) buffer (50 mmol/L Tris, 150 mmol/L NaCl, 1% Triton, 0.10% SDS, and 1% deoxycholate) with complete mini protease inhibitor cocktail (Roche). The IP was incubated at 4°C with continuous...
rotation overnight. The samples were resolved using SDS-PAGE and immunoblot analysis using the α6 integrin–specific antibody A6A (1:10,000) and detected with a HRP-conjugated anti-rabbit antibody. uPAR expression was determined by lysing the cells in RIPA buffer, resolving the samples by SDS-PAGE, and immunoblotting using a uPAR-specific antibody (R&D Systems; 1:2,500) detected by a HRP-conjugated anti-mouse antibody. The proteins were visualized using chemiluminescence (ECL Western Blotting Detection System). The uPAR blots were stripped with 0.2 mol/L NaOH (Sigma) for 5 minutes with rotation at room temperature, rinsed in TBS with Tween (0.01%), and reacted with actin- or tubulin-specific antibodies prior to ECL detection.

Quantitative real-time RT-PCR
Total RNA was isolated using the RNAEasy Mini Kit (Qiagen). TaqMan gene expression probes for uPAR (Hs00182181_m1) and glyceraldehyde-3-phosphate dehydrogenase (GAPDH; Hs99999905_m1) were obtained from Applied Biosystems. Reverse transcriptase PCR (RT-PCR) data were generated using the TaqMan One Step Kit (Applied Biosystems). The REST software program was used to calculate uPAR mRNA levels normalized to GAPDH in each sample. Results included 3 separate experiments conducted in quadruplicate and data were presented as mean ± SD. Statistical analysis was done using a 2-tailed Student’s t test.

siRNA targeting uPAR
The siGENOME siRNA SMART pool targeting uPAR and a control nontargeting siRNA pool were obtained from Dharmacon Research. Transfection was done as suggested by Dharmacon Research with slight modifications. Briefly, 2.0 × 10^5 PC-3 cells were plated in 100-mm tissue culture dishes in IMDM medium supplemented with 10% FBS and transiently transfected the following day with 25 nmol/L uPAR siRNA or control siRNA pools using DharmaFECT reagent 2 for 96 hours. Macrophage conditioned medium was added to the siRNA-transfected PC-3 cells for 24 or 48 hours and the cells were lysed using RIPA buffer.

Invasion assay
The tumor cell invasion assay was done as previously described with slight modifications (19). Briefly, 50 μL of growth factor reduced Matrigel diluted 1:4 with serum-free IMDM media was placed in 8.0-micron cell culture inserts (BD Falcon) and allowed to solidify for 1 hour at 37°C. The inserts were placed into a 24-well plate with 600-μL macrophage conditioned medium supplemented with 10% FBS or IMDM or DMEM supplemented with 10% FBS on the bottom well below the insert. PC-3 (2 × 10^5) cells were placed in the upper insert chamber with 200 μL of serum-free IMDM. Following 24 hours of incubation, inserts were washed in PBS and the Matrigel was removed with a cotton swab. Cells on the underside of the insert were fixed and permeabilized in methanol/acetic acid and stained with 4’,6-diamidino-2-phenylindole (1 μg/mL) for nuclei detection. Cell numbers were counted using a Zeiss Axiophot inverted microscope. Five random images were collected per insert at a magnification of 20×. Results included 3 separate experiments conducted in quadruplicate and data were presented as mean ± SD. Statistical analysis was done using a 2-tailed Student’s t test.

Results
Macrophages stimulated production of the α6 integrin and uPAR expression in PC-3 prostate tumor cells
Figure 1A illustrates the coculturing method for TPA-differentiated HL-60 cells (macrophages) with prostate tumor cells. The HL-60 cells were differentiated into macrophages using TPA and were incubated with CFSE-labeled prostate cells for 24, 48, or 72 hours. HL-60 cells are human myeloid leukemia cells that reproducibly differentiate into macrophages in response to TPA as shown by increased uPAR expression (27) in Supplementary Figure S1. The labeled prostate cells were then sorted from the macrophages using flow cytometry to select CFSE-positive cells (Fig. 1A inset). Figure 1B shows that cell sorting by CFSE expression effectively removes CD13<sup>high</sup> macrophages from CD13<sup>low</sup> prostate tumor cells as shown by the absence of CD13 on prostate cells sorted from macrophages. DU-145 cells were used due to low endogenous CD13 expression when compared with PC-3 cells (28). Minimal macrophage phagocytosis of the prostate cells occurs during the coculture process as shown by flow cytometry analysis of DU-145 and macrophage cocultures shown in Supplementary Figure S2. CD13-labeled macrophages (S2.B) and CFSE-labeled DU-145 cells (S2.C) cultured together show a 3.7% increase in cells expressing both CFSE and CD13 (S2.D). PC-3 cells cocultured with macrophages and cell sorted at 24, 48, and 72 hours exhibited increased α6p at 24 (1.2-fold), 48 (2.8-fold), and 72 hours (1.7-fold; Fig. 1C). These results correlated with increased PC-3 uPAR expression at 24 (3.0-fold), 48 (5.7-fold), and 72 hours (4.5-fold; Fig. 1D).

Macrophages increased PC-3 prostate tumor cell surface uPAR expression
Cleavage of the α6 integrin to α6p is a cell surface event (29–31). Therefore, we next determined whether increased total cell uPAR resulted in increased cell surface expression of the receptor. Flow cytometry indicated an increased number of PC-3 cells expressing cell surface uPAR (Fig. 2A) when compared with PC-3 cells cultured alone (Fig. 2B). Results from 3 independent experiments represented by Figure 2A and B are graphically depicted in Figure 2E and show that macrophages significantly increased the number of PC-3 cells expressing uPAR on the cell surface at 24, 48, or 72 hours. Total cell surface levels of uPAR are increased 8-fold on PC-3 cells and exhibit broad distribution when the PC-3 cells are incubated with macrophages for 72 hours (Fig. 2F).
Conditioned medium from macrophages increased α6p integrin and uPAR expression in prostate tumor cells

We next asked whether macrophage and tumor cell contact was a requirement for macrophage stimulation of uPAR and α6p production in prostate tumor cells by providing only macrophage conditioned medium to the prostate tumor cells. Macrophage conditioned medium increased the conversion of α6 to α6p on both PC-3 (2.5-fold, Fig. 3A, left panel) and DU-145 (2.3-fold, Fig. 3B, left panel) prostate tumor cells lines at 48 hours when compared with undifferentiated HL-60 conditioned medium or IMDM alone. These results correlated with increased PC-3 cell uPAR protein expression (1.5-fold, Fig. 3A, right panel) determined at 48 hours postconditioned medium treatment. DU-145 cells express constitutive levels of uPAR which were not elevated in the presence of macrophage conditioned medium (Fig. 3B, right panel). Results in Figure 3C show that conditioned macrophage medium increased uPAR mRNA expression 2.5-fold in PC-3 cells at 48 hours postconditioned medium treatment.

siRNA targeting uPAR in PC-3 cells prevented macrophage-induced α6p integrin production

PC-3 cells were transiently transfected with siRNA targeting uPAR and a nontargeting pooled siRNA as a control and incubated with macrophage conditioned medium. Depletion of uPAR from PC-3 cells occurs at 96 hours posttreatment with siRNA (Fig. 4A) and inhibits α6p production (Fig. 4B). Under these conditions, macrophage conditioned media does not induce uPAR expression (Fig. 4A) or α6p production (Fig. 4B). These results show that uPAR is required for macrophage-induced cleavage of integrin α6.

Macrophages increased α6p-dependent PC-3 tumor cell invasion

We next asked whether TPA differentiated HL-60 macrophages or human monocytes increased α6p-dependent tumor cell invasion. The PC-3 tumor cells were applied to Matrigel-coated inserts to determine whether invasion was increased in response to macrophage conditioned medium. PC-3 cell invasion through Matrigel was increased by 66% in
Macrophages induced production of α6β1 on prostate tumor cell surfaces in an in vitro coculture model. Macrophage-dependent increased α6p does not require macrophage and tumor cell contact because macrophage conditioned medium induced cleavage of the integrin on prostate tumor cell lines. The observed formation of macrophage-induced α6p is dependent on increased uPAR expression because siRNA-targeting uPAR blocked cleavage of the integrin in the presence of macrophage conditioned medium. Increased prostate tumor cell invasion in response to macrophage conditioned medium is dependent on α6p because a cleavage-blocking antibody (J8H) inhibited prostate tumor cell invasion in in vitro invasion assays. Results from this study show a new mechanism by which macrophages increase the invasive phenotype of prostate tumor cells through modulation of α6β1 integrin cleavage.

Macrophages regulate tumor cell invasion and metastasis by facilitating degradation of the basement membrane surrounding tumor cells by inducing tumor cell proteases (32). The production of α6p suggests that macrophages stimulate a new form of pericellular proteolysis, that is, integrin α6p formation. Presumably, this would be coordinated with immune cells to direct tumor cell invasion.

Figure 3. Differential regulation of uPAR and α6 cleavage in prostate cell lines exposed to macrophage conditioned medium. A, immunoprecipitation and immunoblot analysis for α6 and α6p from PC-3 cells (left) and immunoblot analysis for uPAR (right) treated for 48 hours with control IMDM, macrophage conditioned medium (MΦ CM) or undifferentiated HL-60 medium (HL-60 CM). B, immunoprecipitation and immunoblot analysis for α6 and α6p from DU-145 cells (left) and immunoblot analysis for uPAR (right) treated for 48 hours with control IMDM or MΦ CM. Tubulin is shown as a loading control for uPAR. ImageJ analysis was used to carry out quantification of immunoblot results. The results are representative of more than 3 independent experiments. C, quantitative real-time RT-PCR shows increased uPAR mRNA levels in PC-3 cells treated for 48 hours with MΦ CM when compared with control IMDM medium. The results include 3 independent experiments conducted in triplicate (P < 0.05). Columns, mean; bars, SD. IB, immunoblotting.

Discussion

response to conditioned medium from TPA-differentiated HL-60 cells, when compared with undifferentiated HL-60 cell conditioned medium, and by 93%, when compared with IMDM medium supplemented with 10% FBS (Fig. 5A). PC-3 invasion was increased by 93% in the presence of human monocyte conditioned medium when compared with control medium (Fig. 5B). Increased PC-3 cell invasion in response to macrophage or human monocyte conditioned medium was inhibited by 81% and 54%, respectively, when the prostate cells were treated with the α6 cleavage-blocking antibody J8H (Fig. 5A and B).

Figure 4. siRNA–targeting uPAR inhibited macrophage-induced α6p on prostate tumor cells. A, immunoblot analysis was done to determine uPAR expression in PC-3 cells transfected with siRNA-targeting uPAR. In lane 1, PC-3 cells treated with siRNA control (siCON) were incubated with MΦ CM to show increased uPAR expression in the presence of MΦ CM. In lanes 2 and 3, the cells were incubated with a siCON or uPAR-specific siRNA (siuPAR) for 96 hours followed by incubation in IMDM control medium or MΦ CM for an additional 48 hours prior to cell lysis and protein isolation. In lanes 4 and 5, the PC-3 cells were transiently transfected with siCON or siuPAR for 96 hours and IMDM or MΦ CM were added to the cells with fresh siCON or siuPAR for an additional 48 hours prior to cell lysis and protein isolation. B, integrin α6 was immunoprecipitated from cell lysates and immunoblot analysis was done to detect expression of the integrin. IB, immunoblotting.
Macrophage Induced α6 Integrin Cleavage in Prostate Cancer

Figure 5. J8H inhibits macrophage- and human monocyte-induced prostate cancer cell invasion through Matrigel. A, PC-3 cells were incubated with IMDM, HL-60 conditioned medium (HL-60 CM), and TPA differentiated HL-60 conditioned medium (HL-60 M6 CM) in the presence or absence of the J8H α6 cleavage-blocking antibody (50 μg/mL) in a Matrigel invasion assay. HL-60 M6 CM significantly increased PC-3 tumor cell invasion which was blocked by the J8H antibody. B, human monocyte conditioned medium (HMCM) significantly increased PC-3 invasion which was blocked by the J8H antibody. Results are expressed as the mean of 3 independent experiments conducted in quadruplicate. Columns, means; bars, SD. *, P < 0.05 for PC-3 invasion induced by macrophage or HMCM compared with all other treatment groups. Approximately 600 and 250 cells are represented by 100% invasion for HL-60 macrophage conditioned media and monocyte conditioned media, respectively.

and metastasis by secretion of cytokines which affect tumor cell chemotaxis (4, 7). The presence of highly motile macrophages in regions surrounding vessels which promote tumor cell intravasation into blood vessel walls in metastatic mammary tumors in vivo has been reported (33), and it is thought that the presence of macrophages along the vessel walls causes tumor cell intravasation as they react to the abundance of chemotactic factors produced by the macrophages (34). Investigation of the role macrophages play in regulating tumorigenesis has been shown in vitro and in vivo. In vitro coculture models have established the role of macrophages in regulating invasion (32) growth (35) and survival (36). Specific to prostate cancer, it has been identified that macrophage interactions with tumor cells promote androgen resistance (37) and increased presence of macrophages in primary tumors and contributes to metastatic tumor progression (38). Recent evidence has shown that α6 integrin is expressed in mammary tumors (39). Increased expression of α6 integrin has also been reported (50).

In this study, tumor cell line and macrophage coculture showed that macrophage increased α6 expression. Macrophage conditioned medium induced both uPAR mRNA and protein and integrin α6 on PC-3 prostate tumor cells, indicating transcriptional regulation of uPAR which will direct α6 cleavage in tumor cells. Interestingly, TAMs are recruited to poorly vascularized, hypoxic and necrotic areas of tumors (51) and secrete factors such as VEGF to stimulate angiogenesis (52). VEGF increases uPAR mRNA levels indicating transcriptional control of uPAR in the presence of this growth factor (53). It is also pertinent that VEGF and uPAR are both transcriptionally regulated by hypoxia-inducible factor 1 alpha (54, 55), a hypoxia-regulated transcription factor which activates genes required for critical aspects of tumor progression. TPA-differentiated HL-60 cells exhibit increased expression of VEGF upon TPA treatment (56), which could be a potential regulator of uPAR transcription in our system. Depletion of uPAR from PC-3 cells using silencing RNA indicated the requirement for tumor cell–derived uPAR in cleavage of α6β1 in the

www.aacrjournals.org Mol Cancer Res; 9(10) October 2011 1325

Published OnlineFirst August 8, 2011; DOI: 10.1158/1541-7786.MCR-11-0080
presence of macrophage conditioned medium. These results show that tumor-infiltrating macrophages stimulate prostate tumor invasion through a coordinated mechanism of uPAR induction and subsequent integrin cleavage, a process which does not require direct contact between tumor cells and the TAMs. These results suggest that although prostate tumors can exhibit low levels of macrophage infiltration as previously reported (15), the TAM mediated paracrine regulation of tumor cell uPAR and α6β1 may be expansive. Notable contributing factors may include TAM-secreted cytokines such as IL-1β (51, 57) or growth factors including epidermal growth factor (58).

It is intriguing that a subpopulation of PC-3 cells exists which does not exhibit increased uPAR expression in response to macrophages (Fig. 2A). This shows differential regulation of tumor cell responses to macrophages and may be a useful clue for determining whether an aggressive macrophage-responsive phenotype exists in prostate cancer patients.

Furthermore, DU-145 cells have constitutive expression of uPAR and exhibit increased α6p production in response to macrophages. These results suggest that other components of the uPA/uPAR axis may increase α6 cleavage in DU-145 cells. Tumor cell uPA or suppression of plasminogen activator inhibitor-1 are likely candidates responsive to macrophage-derived signals in cells exhibiting constitutive levels of the uPAR receptor. The increased availability of uPA secreted by macrophages may also contribute to the observed increase in integrin α6p formation on DU-145 cells. The functional role of macrophage-dependent increased α6p was shown in in vitro invasion assays (Fig. 5) which indicated that blocking α6 cleavage impeded prostate tumor cell invasion in response to macrophages. This antibody does not affect cell adhesion (59). Therefore, these results highlight a novel mechanism by which a tumor-specific modification of a cell surface receptor induced by the stromal environment can be targeted to halt invasive progression of this disease.

In summary, we have identified that macrophages increased uPAR and α6p integrin on PC-3 cells and α6p on DU-145 cells. The role of the uPA in α6p formation to promote prostate cancer cell migration, invasion, and metastasis to bone (17, 19, 29, 31) has been established. Reagents developed in our laboratory have shown that this cleavage event and α6 integrin-dependent tumor cell migration and metastasis are inhibited when this function of the receptor is blocked (19, 60). Here, we show that TAM directly contributes to an invasive tumor cell phenotype by modulating α6p through the uPA receptor, uPAR. Identifying contributing factors in the tumor microenvironment which modulate this cleavage event on tumor cells is necessary for determining alternative therapeutic targets for a multimodality approach to inhibit the invasion steps of metastasis. Inhibition of TAMs combined with specific blockade of integrin cleavage and uPAR will be essential for controlling metastatic spread in prostate cancer.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Acknowledgments

We thank Dr. Terry Landowski for her technical assistance in human monocyte isolation procedures.

Grant Support

This work was supported in part by NIH grants R01 CA159406 and P30 CA23074. The Arizona Cancer Center Genomics Core is supported by the Southwest Environmental Health Sciences Center NIEHS grant E06694. The Genomics and Flow Cytometry Cores are supported by the Arizona Cancer Center NIH grant CA23074. C.P. Sandoval was supported by the T34 GM 8718 grant and H. Chopra was supported by the Howard Hughes Medical Institute Grant 5205889.

The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked advertisement in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

Received February 14, 2011; revised June 21, 2011; accepted July 26, 2011; published OnlineFirst August 8, 2011.

References


Macrophage-Dependent Cleavage of the Laminin Receptor $\alpha 6\beta 1$ in Prostate Cancer

Isis C. Sroka, Cynthia P. Sandoval, Harsharon Chopra, et al.