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Et al.

REVIEW

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Abstract

Integrins, which are transmembrane receptors for extracellular matrix proteins, play a key role in cell survival, proliferation, migration, gene expression, and activation of growth factor receptors. Their functions and expression are deregulated in several types of cancer, including prostate cancer. In this article, we review the role of integrins in prostate cancer progression and their potential as therapeutic targets.

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Introduction

Prostate cancer develops through a series of defined states: prostatic intraepithelial neoplasia (PIN), high-grade PIN lesions, invasive cancer, and an androgen-independent state (Scher & Heller 2000, Culig & Bartsch 2006, Dehm & Tindall 2006). These defined states arise through multiple alterations in normal cell functions (Mimeault & Batra 2006). Among the alterations described in prostate cancer are abnormal expression and functions of integrins and of their extracellular matrix (ECM) ligands (Boudreau & Bissell 1998, Fornaro *et al*. 2001). The resulting abnormal cellular interactions with the ECM promote cell proliferation, migration, and differentiation and contribute to cancer progression through the above-described states (Boudreau & Bissell 1998, Fornaro *et al*. 2001, Knudsen & Miranti 2006). We review here several studies describing aberrations in the normal expression and functions of integrins in prostate cancer, specifically those that are likely to be relevant to the progression of this disease. Due to space constraints, we will not be able to review all the *in vitro* studies published in this area of research.

Integrin deregulation in prostate cancer

In prostate cancer, tumor cells express an abnormal integrin repertoire and are surrounded by a markedly aberrant ECM. These changes have profound consequences, given the ability of each integrin to regulate specific cell functions. At this time, 24 members of the integrin family, 18 α and 8 β subunits have been described; for a detailed description of the 24 members and for their ECM ligands, the reader should refer to Hynes 2002 and Alam *et al*. 2007.

Several studies report deregulation of integrin expression as prostate cancer progresses to an advanced stage (Fornaro *et al*. 2001, Edlund *et al*. 2004, Knudsen & Miranti 2006; Table 1). Most α and β subunits have been shown to be downregulated in prostate cancer.

Among the α subunits, several reports show that the α_3, α_4, α_5, α_7, and α_v are downregulated, α_{IIb} is upregulated and α_2 and α_6 are aberrantly expressed as discussed below, whereas there are no reports on the remaining subunits (Table 1). A unique expression pattern has been shown for α_2, which is downregulated in prostate cancer but upregulated in lymph node metastases when compared with primary lesions (Bonkhoff *et al*. 1993). An extensive analysis of α_6 expression in prostate cancer has been reported; α_6 expression is maintained in prostate neoplasm, but its expression becomes more intense and its density at sites of contact with the basement membrane diminishes with increasing histologic grade (Bonkhoff *et al*. 1993).

Among the β subunits, β_1, β_3, and β_6 are upregulated in human prostate cancer. β_{1C} and β_4 are downregulated, whereas no reports are available for β_5, β_7, and β_8 (Table 1).

Five β_1 variant subunits, β_{1A}, β_{1B}, β_{1C}, $\beta_{1C\text{-}2}$ and β_{1D}, generated by alternative splicing, have been described. Two variants, β_{1C} and β_{1A}, have been shown to be

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Table 1 Integrin deregulation in human prostate cancer

	Sample; method	Deregulated expression	References
α Subunit			
α_2	Tissue specimens; IHC	Downregulated in adenocarcinoma[a]; upregulated in metastases	Bonkhoff *et al.* (1993) and Nagle *et al.* (1994)
α_3, α_4, α_5	Tissue specimens; IHC	Downregulated in adenocarcinoma	Nagle *et al.* 1994
α_6	Tissue specimens; IHC, TEM	Polarized distribution in benign, less polarized in HGPIN, not polarized in lymph node metastases; upregulated in metastases	Bonkhoff *et al.* (1993), Knox *et al.* (1994) and Nagle *et al.* (1995)
α_7	Tissue specimens; IHC, sequencing of genomic DNAs and cDNAs	Downregulated in adenocarcinoma; also mutated in adenocarcinoma and recurrent adenocarcinoma	Ren *et al.* (2007)
α_{IIb} (truncated)	Tissue specimens; IHC	Expressed in adenocarcinoma; absent in normal tissue	Trikha *et al.* (1998*a*,*b*)
β Subunit			
β_1	Tissue specimens; IHC	Upregulated in adenocarcinoma; redistributed with progression	Knox *et al.* (1994), Murant *et al.* (1997) and Goel *et al.* (2007)
β_{1C}	Tissue specimens; IHC	Downregulated in adenocarcinoma[b]	Fornaro *et al.* (1996, 1998, 1999) and Perlino *et al.* (2000)
β_3	Freshly isolated cells and primary cultures, tissue specimens; FACS, Immunoblotting, IHC	Expressed in adenocarcinoma and metastatic lesions; absent in normal cells	Zheng *et al.* (1999)
β_4	Tissue specimens; IHC	Downregulated in adenocarcinoma[c]	Nagle *et al.* (1995), Allen *et al.* (1998) and Davis *et al.* (2001)
β_6	Tissue specimens; IHC	Upregulated in adenocarcinoma and metastases; absent in normal cells	Li *et al.* (2007*a*)

Studies performed using cell lines are not included. IHC, immunohistochemistry; TEM, transmission electron microscopy; FACS, fluorescence-activated cell sorting.
[a]α_2 was found to be downregulated in 70% cases with grade II and III tumors.
[b]β_{1C} downregulation was observed regardless of the tumor Gleason grade (grade II to V).
[c]β_4 downregulation was observed regardless of the tumor Gleason grade (grade II to V).

expressed in prostatic epithelium. β_{1C} is shown to be expressed at both protein and mRNA levels in normal prostatic epithelial cells, but is markedly downregulated in adenocarcinoma (Fornaro *et al.* 1996, 1998, 1999, Perlino *et al.* 2000). β_{1A} has been found to be consistently upregulated in human prostate cancer (Knox *et al.* 1994, Murant *et al.* 1997, Goel *et al.* 2007) as well as in a mouse model designated TRAMP (transgenic adenocarcinoma of mouse prostate) (Goel *et al.* 2005). Since β_{1A} associates with many α integrins and α_2 and α_6 are elevated in prostate cancer, it is conceivable that β_{1A} will be present predominantly as $\alpha_2\beta_1$ and/or $\alpha_6\beta_1$ heterodimeric complexes (Bonkhoff *et al.* 1993, Fornaro *et al.* 2001, Alam *et al.* 2007). The finding that the expression of the β_{1A} integrin variant is upregulated and is necessary for cells to be able to grow in an anchorage-independent manner, point to the important role that β_{1A} integrin may have during prostate cancer progression and will be helpful in formulating new therapeutic strategies (Goel *et al.* 2005). Recently, increased levels of β_1 and its ligand, fibronectin, have been shown to be associated with decreased survival of breast cancer patients (Yao *et al.* 2007), but this finding has not been reported in prostate cancer.

Upregulation of β_3 and β_6 integrin variants has been described. Zheng *et al.* (1999) used human prostate cancer cells isolated from 16 surgical specimens, to show that these cells express $\alpha_v\beta_3$, whereas normal prostate epithelial cells do not. Similarly, $\alpha_v\beta_6$ (Azare *et al.* 2007, Li *et al.* 2007*a*) and the truncated α_{IIb} integrin variant (Trikha *et al.* 1998*a*) were found to be expressed in adenocarcinoma.

The β_1, β_3, and β_6 integrin subunits are known to localize in focal contacts and to mediate spreading and cytoskeletal rearrangements in normal cells (Hynes 2002, Alam *et al.* 2007). However, when we either downregulated or upregulated these subunits by siRNA or ectopic expression analysis, we showed that cancer cell spreading was not affected. These results demonstrate that the ability of β_1, β_3, and β_6 subunits to promote cancer progression is independent of cell spreading.

Expression of β_3 and β_1 subunits activates specific signaling pathways and support distinct cancer cell functions. We have discovered that β_3 is uniquely required in cancer cells for increasing cdc2 levels as well as cdc2 kinase activity. These effects are specific for β_3 and are not observed for β_6, although both subunits associate with the same α subunit, α_v. Higher levels of cdc2 result in increased cell migration mediated by specific association of cdc2 with cyclin B2 and phosphorylation of caldesmon, a substrate of cdc2. We also demonstrate that cdc2 and caldesmon are localized in the membrane ruffles of motile cells. These results show that cdc2 acts as a downstream effector of the $\alpha_v\beta_3$ integrin and that it promotes cancer cell migration (Manes *et al*. 2003). In contrast, β_1 integrin expression did not increase cancer cell motility or cdc2 levels; it appeared, predominantly, to modulate cell proliferation and survival (Manes *et al*. 2003, Goel *et al*. 2005). Analysis of the mechanism by which β_1 may promote tumor growth *in vivo* shows that β_1 is uniquely required in cancer cells for localization, expression, and function of a surface receptor – insulin-like growth factor (IGF) type 1 receptor (IGF-IR) which is known to support cancer cell proliferation and survival (Goel *et al*. 2004, 2005). The mechanism proposed for the control of β_1 integrin on IGF-IR activity involves the recruitment of specific adaptors to the plasma membrane by β_1, thus increasing the concentration of specific adaptors proximal to the growth factor receptor (Goel *et al*. 2004). Evidence is provided in this study that the β_1 cytodomain plays an important role in mediating β_1 integrin association with either IRS-1 or Grb2-associated binder1 (Gab1)/SH2-containing protein-tyrosine phosphate 2 (Shp2), downstream effectors of IGF-IR: specifically, β_{1A} associates with IRS-1 and β_{1C} with Gab1/Shp2 (Goel *et al*. 2004, 2005). In conclusion, the β_3 and β_1 integrins facilitate activation of selective signaling pathways that support cancer progression.

Additional evidence indicates that PTEN, a tumor suppressor frequently deleted or mutated in prostate cancer (Li *et al*. 1997, Steck *et al*. 1997), may play a role in the regulation of cell migration on integrin substrates (Tamura *et al*. 1998, Wu *et al*. 2007). The mechanism through which it regulates cell migration is not known, although it is likely to utilize PTEN phosphatase activity, which has the ability to dephosphorylate inositol phospholipids such as PIP3 and, as a consequence, to negatively regulate activation of a modulator of motility on integrin substrates, AKT (Alam *et al*. 2007).

Overall, these findings indicate that the expression of selective integrin subunits is deregulated during prostate cancer progression and that these subunits are potential diagnostic markers in prostate cancer.

In vivo integrin functions in prostate cancer

As modulators of cell survival, migration, invasion, and angiogenesis (Parise *et al*. 2000, Fornaro *et al*. 2001, Tantivejkul *et al*. 2004, Moschos *et al*. 2007) integrins promote progression of many types of cancer including prostate cancer (Fornaro *et al*. 2001). Preclinical studies (Park *et al*. 2006, Van Aarsen *et al*. 2008, Cariati *et al*. 2008) that have utilized inhibitory antibodies, RGD peptides or siRNA to block integrin functions or expression have shown promising results. We review below the evidence supporting a role for integrins in prostate cancer growth and metastasis *in vivo*.

Tumor growth and metastasis

Primary tumor growth has been shown to be affected by integrin expression. Expression of the β_1 cytoplasmic variant, β_{1C}, which is downregulated in prostate cancer, completely prevents tumor growth by inhibiting IGF-IR signaling (Goel *et al*. 2004). It has also been reported that the expression of α_7 in prostate cancer cells injected subcutaneously in SCID mice suppresses tumor growth (Ren *et al*. 2007). This observation is relevant to the human disease as analysis of α_7 in human prostate cancer reveals that α_7 is downregulated in this type of cancer and is mutated in 57% of prostate cancers; in addition, mutations in this subunit are associated with increased cancer recurrence (Ren *et al*. 2007). Pawar *et al*. (2007) show that growth of tumors treated with fractionated doses of irradiation (3 Gy$\times$10 days) is inhibited in PC3 cells expressing a mutated non-cleavable form of α_6 integrin. Thus, blocking integrin cleavage *in vivo* may be efficacious for increasing responsiveness to irradiation of pro-metastatic human prostate cancer.

The metastatic process is likely to be dependent on the ability of cancer cells to migrate and invade, but it is also dependent on the ability of these cells to grow in distant sites (Fornaro *et al*. 2001, Felding-Habermann 2003). All these functions are mediated by integrins. Early studies using PC3 and DU145 cells, both of which express integrin $\alpha_{IIb}\beta_3$, suggest a role for $\alpha_{IIb}\beta_3$ in prostate cancer metastasis. These cell lines, implanted subcutaneously or intraprostatically into SCID mice, prove tumorigenic, but only DU145 cells injected intraprostatically metastasized. An analysis performed on the cells described above using an

antibody to $\alpha_{IIb}\beta_3$ shows a higher expression of $\alpha_{IIb}\beta_3$ in DU145 tumor cells isolated from the prostate when compared with DU145 tumor cells from the subcutis. These data suggest a role for $\alpha_{IIb}\beta_3$ in the metastatic progression of prostatic adenocarcinoma (Trikha *et al.* 1998*b*). De *et al.* (2003) use secreted protein acidic and rich in cysteine (SPARC)-deficient mice and show that SPARC selectively supports the migration of highly metastatic as opposed to less metastatic cancer cell lines to bone in an $\alpha_v\beta_3$- and $\alpha_v\beta_5$-dependent manner.

It should be stressed that ECM proteins are routinely cleaved and their fragments bind integrins (Giannelli *et al.* 1997, Hynes 2002). The relative ratio of matrix metalloproteinases, cell surface proteases, such as hepsin (Klezovitch *et al.* 2004) which is upregulated in prostate cancer, and protease inhibitors such as maspin known to be a metastasis suppressor (Li *et al.* 2007*a*,*b*, Luo *et al.* 2007), contribute to ECM protein cleavage. This allows tumor cells to invade connective tissues and travel out of the vasculature to distant sites (Zucker *et al.* 2000).

Bone is the most frequent metastatic site for this disease. Bisanz *et al.* (2005) illustrate a positive role for α_v integrins on prostate tumor survival in the bone. Analysis of human prostate cancer bone xenografts shows that intratumoral administration of liposome-encapsulated human α_v-siRNAs significantly inhibits the growth of PC3 tumors in bone and increases apoptosis of prostate tumor cells. Further studies, implicating integrin α_v in prostate cancer metastasis in bone, by McCabe *et al.* (2007) indicate that expression of fully functional $\alpha_v\beta_3$ enable tumor growth in bone whereas inactive or constitutively active mutants do not. They demonstrate that $\alpha_v\beta_3$ integrin activation on tumor cells is essential for the recognition of key bone-specific matrix proteins. These data suggest that the $\alpha_v\beta_3$ integrin modulates prostate cancer growth in distant metastasis. Other studies implicate $\alpha_2\beta_1$ as a possible modulator of prostate cancer metastasis to bone matrix proteins. Hall *et al.* (2006) tested whether prostate cancer bone metastasis is mediated by binding to type I collagen, an abundant bone protein that binds $\alpha_2\beta_1$. To directly test this, a collagen-binding variant of human LNCaP cells, $LNCaP_{col}$, was created and injected into the tibia of nude mice. After 9 weeks, 53% of mice injected with $LNCaP_{col}$ develop bone tumors whereas none of the mice injected with parental LNCaP had signs of bone lesions.

Finally, it should be noted that adhesion of highly metastatic prostate cancer cells to bone marrow endothelial cells require additional ECM components that do not bind integrins. Among others, a matrix of a secreted glycosaminoglycan component of the ECM, hyaluronan (HA), is required to provide specific adhesion of highly metastatic prostate cancer cells to bone marrow endothelial cells (Simpson *et al.* 2002*a*). This molecule may act through regulation of cancer cell growth (Simpson *et al.* 2002*b*).

Tumor angiogenesis

Angiogenesis, a process critical for tumor formation and growth (Nicholson & Theodorescu 2004, Jimenez *et al.* 2006, Sakamoto *et al.* 2008), is regulated by integrin functions (Hynes 2007). $\alpha_v\beta_3$ and $\alpha_v\beta_5$, by using a crosstalk with growth factor signaling pathways (Alam *et al.* 2007), regulate angiogenesis. Sun *et al.* (2007) have evaluated the efficacy of a new camptothecin conjugate, JF-10-81, an anti-angiogenic agent, in a prostate cancer mouse model. JF-10-81 blocks cancer cell adhesion *in vivo* and angiogenesis in C57B1/N mice and reduces expression of $\alpha_v\beta_3$ and $\alpha_v\beta_5$ on PC3 cells which implies an inhibitory effect on angiogenesis through an $\alpha_v\beta_3$- and $\alpha_v\beta_5$-dependent mechanism. A study that analyzes a knock-in mouse expressing a mutant β_3 that cannot undergo tyrosine phosphorylation shows that β_3-deficient mice have impaired capillary formation in response to VEGF stimulation, and thus form smaller prostate tumors than their wild-type counterparts. These observations highlight the role of vascular $\alpha_v\beta_3$ in prostate cancer through modulation of angiogenesis (Mahabeleshwar *et al.* 2006). Finally, a promising avenue is presented by a study showing that the treatment of a PC3 xenograft with an $\alpha_v\beta_3$ antagonist (S247, a cyclic RGD peptidomimetic) in combination with radiation, leads to enhanced anti-angiogenic and anti-tumor effects when compared with either therapy alone (Abdollahi *et al.* 2005).

The use of integrin inhibitors is likely to affect both cancer cell survival and angiogenesis since integrins are expressed by tumor cells as well as by endothelial cells. Although it is hard to discriminate between an effect on tumor growth and an effect on angiogenesis, a maximal response of these inhibitors can be predicted when the targeted integrin is expressed by both tumor and endothelial cells.

These preclinical studies which take advantage of the available mechanistic investigations, have prompted several clinical studies (described below), aimed at identifying novel molecular strategies to block prostate cancer progression.

Integrin inhibitors in clinical trials

Clinical trials that evaluate the effect of integrin antagonists as prostate cancer therapeutics are

ongoing. Available reports at this time indicate that the α_v integrins are promising therapeutic targets in prostate cancer. Two clinical trials using Cilengitide, a cyclic Arg-Gly-Asp peptide that inhibits $\alpha_v\beta_3$ and $\alpha_v\beta_5$ (Beekman *et al*. 2006), an antagonist of α_v integrins, are in progress. Cilengitide is being evaluated in two Phase II clinical trials. In one study (NCI 6735), one dose of 2000 mg given intravenously twice weekly is being evaluated in men with androgen-independent prostate cancer and non-metastatic disease. In another study, (NCI 6372), two dose levels of Cilengitide, 500 and 2000 mg, are administered twice weekly in men with androgen-independent metastatic prostate cancer (Beekman *et al*. 2006). Antibodies to α_v integrins are also being evaluated in two clinical trials. The first utilizes CNTO 95, a monoclonal antibody that inhibits α_v integrins and blocks tumor growth (Chen *et al*. 2007). In Phase I, CNTO 95 (10 mg/kg, once a week) in combination with standard drugs docetaxel (75 mg/m^2, every 3 weeks) and prednisone (twice a day) appears to be well tolerated in hormone refractory prostate cancer patients (Chu *et al*. 2007). A Phase II clinical trial (NCT00537381) is also in progress with CNTO 95 (10 mg/kg, once a week) in combination with docetaxel (75 mg/m^2, every 3 weeks) and prednisone (twice a day) in metastatic hormone refractory prostate cancer patients. The second trial utilizes MEDI-522, a humanized monoclonal IgG1 antibody directed against the $\alpha_v\beta_3$ integrin. MEDI-522 blocks the binding of ligands, such as vitronectin, to $\alpha_v\beta_3$ integrin (McNeel *et al*. 2005). A Phase II, randomized, open-label, two-arm, multicenter study of MEDI-522, in combination with docetaxel, prednisone, and zoledronic acid in the treatment of patients with metastatic androgen-independent prostate cancer (NCT00072930) is ongoing. Results from these studies will pave the way to new and improved strategies to prevent prostate cancer in humans.

Conclusions

Prostate cancer accounts for a significant cancer burden in the USA, where it is projected to result in over 28 660 deaths and more than 186 320 new cases in 2008 (Jemal *et al*. 2008). While substantial advances have been made in diagnosing and treating this disease, the molecular mechanisms that promote prostate cancer progression remain to be fully investigated (Pomerantz & Kantoff 2007). The studies reviewed here show that prostate cancer progression has been correlated with expression of specific integrin subunits and is influenced by deregulation of selective subunits, which then activate distinct signaling pathways (Fornaro *et al*. 2001). Although the molecular pathways by which integrins contribute to cancer progression need to be fully elucidated, designing new therapeutic approaches for prostate cancer based on inhibiting integrin expression, Ligand binding or downstream signaling is likely to be a successful strategy.

Several questions remain to be answered in this under-investigated area of research. The mechanisms by which integrins are regulated need to be characterized by focusing on modulators of integrin expression. Yet another promising avenue of research is to elucidate the role of integrins in promoting proliferation of prostate cancer stem cells, in particular, $\alpha_2\beta_1$ appears to be interesting since it is highly expressed in these cells (Collins *et al*. 2005, Mimeault *et al*. 2007). Finally, an under-investigated area in prostate cancer research is the cross talk between bone microenvironment and metastasis (Mohla 2004), to which the interactions between integrins and their ECM ligands are likely to contribute significantly. Since integrins mediate the interactions between tumor cells and bone microenvironment and facilitate growth in bone, a potential application of the use of integrin inhibitors is to prevent prostate cancer bone lesions (Waltregny *et al*. 2000, Pecheur *et al*. 2002, Karadag *et al*. 2004, Hall *et al*. 2006). These lesions are osteoblastic or osteolytic and are frequently detected in prostate cancer patients (over 80% of prostate cancer patients have established bone metastasis at autopsy (Koeneman *et al*. 1999)). A recent study has shown that the $\alpha_v\beta_3$ integrin promotes bone gain mediated by prostate cancer cells that metastatize to the bone and point to $\alpha_v\beta_3$ as a potential therapeutic target to block prostate cancer osteoblastic lesions (Keller & Brown 2004, McCabe *et al*. 2007). Besides therapeutic applications, other uses of integrin inhibitors are in the area of imaging and specific delivery of a drug to cancer cells (Chen *et al*. 2001, Moschos *et al*. 2007, Li *et al*. 2008).

In conclusion, these investigations indicate that the clinical use of integrin inhibitors is likely to be a successful strategy to prevent all stages of cancer progression from tumor growth to metastasis.

Declaration of interest

The authors declare that there is no conflict of interest that would prejudice the impartiality of this work.

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