Crosstalk between epithelial-mesenchymal transition and castration resistance mediated by Twist1/AR signaling in prostate cancer

Masaki Shiota1, Momoe Itsumi1, Ario Takeuchi1, Kenjiro Imada1,2, Akira Yokomizo1, Hidetoshi Kuruma3, Junichi Inokuchi1, Katsunori Tatsugami1, Takeshi Uchiumi4, Yoshinao Oda2 and Seiji Naito1

Departments of 1Urology, and 2Anatomic Pathology, Graduate School of Medical Sciences, Kyushu University, 3-1-1 Maidashi, Higashi-ku, Fukuoka 812-8582, Japan
3Department of Urology, School of Medicine, Jikei University, Tokyo 105-0003, Japan
4Department of Clinical Chemistry and Laboratory Medicine, Graduate School of Medical Sciences, Kyushu University, 3-1-1 Maidashi, Higashi-ku, Fukuoka 812-8582, Japan

Abstract

Although invasive and metastatic progression via the epithelial-mesenchymal transition (EMT) and acquisition of resistance to castration are both critical steps in prostate cancer, the molecular mechanism of this interaction remains unclear. In this study, we aimed to elucidate the interaction of signaling between castration resistance and EMT, and to apply this information to the development of a novel therapeutic concept using transforming growth factor-β (TGF-β) inhibitor SB525334 combined with androgen-deprivation therapy against prostate cancer using an in vivo model. This study revealed that an EMT inducer (TGF-β) induced full-length androgen receptor (AR) and AR variant expression. In addition, a highly invasive clone showed augmented full-length AR and AR variant expression as well as acquisition of castration resistance. Conversely, full-length AR and AR as well as Twist1 and mesenchymal molecules variant expression were up-regulated in castration-resistant LNCaP xenograft. Finally, TGF-β inhibitor suppressed Twist1 and AR expression as well as prostate cancer growth combined with castration. Taken together, these results demonstrate that Twist1/AR signaling was augmented in castration resistant as well as mesenchymal-phenotype prostate cancer, indicating the molecular mechanism of mutual and functional crosstalk between EMT and castration resistance, which may play a crucial role in prostate carcinogenesis and progression.

Key Words
- androgen-deprivation therapy
- androgen receptor
- castration resistance
- epithelial-mesenchymal transition
- prostate cancer
- Twist1

Introduction

Prostate cancer is the most common non-cutaneous cancer and the second leading cause of cancer-related mortality among the male population in Western countries. Most prostate cancers are initially dependent on androgens for tumor growth and respond well to androgen-deprivation therapy (ADT), which is the gold
Endocrine-Related Cancer

transcription factor Twist1 is implied. and castration resistance induced by the common cancer. Thus, a molecular relationship between EMT castration resistance to androgen-dependent prostate tissues (Shiota 2010, 2014). In addition, Twist1 was up-regulated following androgen ablation in human prostate cancer (Sharifi a). The mechanism for aberrant AR signaling is attributable to AR overexpression, AR mutations, AR co-regulators, AR activation by intra-cellular signal-transduction pathways, de novo androgen synthesis, and AR splice-variants (Chen et al. 2008). After becoming castration resistant, effective therapeutic options are limited, and the end result is often fatal. Accordingly, the development of a novel strategy for preventing the progression to castration resistance and for treating CRPC is urgently required (Shiota et al. 2013a).

Acquisition of migratory properties is a prerequisite for cancer to invade into cancer-surrounding tissue. Cancer invasion requires dramatic morphological and functional alterations, termed epithelial-mesenchymal transition (EMT), whereby cancer cells lose epithelial characteristics, but acquire a mesenchymal phenotype (Thiery & Sleeman 2006). E-cadherin is an adhesion molecule and an epithelial marker, the loss of which leads to increased cellular invasion and motility (Schmalhofer et al. 2009). Conversely, N-cadherin, fibronectin, and vimentin are mesenchymal markers that provide mesenchymal abilities (Zeisberg & Neilson 2009). The loss of epithelial cell markers such as E-cadherin with concomitant gain of mesenchymal markers, including N-cadherin, fibronectin, and vimentin, are hallmarks of EMT. The expression of EMT-related molecular markers is regulated by several E-box (5′-CANNTG-3′)-binding transcription factors (Shiota et al. 2012a).

The basic helix-loop-helix transcription factor Twist1 is known to regulate the expression of target genes and to promote EMT (Ansieau et al. 2010). We have previously shown that Twist1 promoted prostate cancer growth through the regulation of AR expression (Shiota et al. 2010, 2014). In addition, Twist1 was up-regulated following androgen ablation in human prostate cancer tissues (Shiota et al. 2012h), suggesting that Twist1 confers castration resistance to androgen-dependent prostate cancer. Thus, a molecular relationship between EMT and castration resistance induced by the common transcription factor Twist1 is implied.

Clinical findings have also shown that highly metastatic prostate cancer is more likely to become castration resistant (Cooperberg et al. 2009). Furthermore, circulating-tumor cell (CTC) counts may predict therapeutic effect and increase along with the development of castration resistance after suppression by ADT, suggesting that CRPC may easily form in metastatic regions via CTC dissemination (Danila et al. 2011, Miyamoto et al. 2012). However, to date, the biological and molecular basis of the relationship between EMT and castration resistance remains obscure. Therefore, in this study, we aim to define the mechanism by which Twist1 mediates the mutual regulation between EMT and castration resistance through regulation of AR signaling.

Materials and methods

Cell culture

Human prostate cancer LNCaP and 22Rv1 cells were obtained from American Type Culture Collection (Manassas, VA, USA) and authenticated by STRS analysis. C4-2 cells which were established from LNCaP cells and commonly utilized cell lines authenticated by whole-genome and whole-transcriptome sequencing on an Illumina Genome Analyzer IIx platform (Lamoureux et al. 2011) were kindly provided by Dr Martin Gleave (Vancouver Prostate Centre, Vancouver, BC, Canada). Cells were cultured in Roswell Park Memorial Institute (RPMI) 1640 media, which was purchased from Life Technologies Corporation supplemented with 10% fetal bovine serum (FBS). All cell lines were passaged <35 times before use. 22Rv1/transforming growth factor (TGF) cells were established by long-term culture in the appropriate medium containing 5 ng/ml of human TGF-β1 recombinant protein (RD Systems, Minneapolis, MN, USA). Highly invasive clones of 22Rv1 cells (22Rv1/H1) were established by four selection iterations of invaded cells through an 8-μm pore matrigel chamber (BD Biosciences, San Jose, CA, USA) and maintained in RPMI1640 media. The cell lines were maintained in a 5% CO₂ atmosphere at 37 °C. When using TGF-β1 and dihydrotestosterone (DHT), media were changed to serum free or 10% charcoal-stripped serum (CSS) supplemented respectively.

Antibodies and reagents

Antibodies against AR (N-20, sc-816) which recognizes N-terminus of AR protein and Twist1 (sc-81417) were purchased from Santa Cruz Biotechnology. Anti-phosphorylated Smad2/3 (p-Smad2/3; #8828) and anti-Smad3/2 (#8685) antibodies were obtained from Cell
Signaling Technology (Cambridge, MA, USA). Antibodies against E-cadherin (#610181), N-cadherin (#610920), fibronectin (#610077), and vimentin (#550513) were purchased from BD Biosciences. Anti-β-actin (A3854) and anti-AR V7 (AG10008) antibodies were obtained from Sigma–Aldrich and Precision Antibody (Columbia, MD, USA) respectively. Anti-AR V7 (AG10008) antibody from Precision Antibody was utilized for blotting full-length AR and AR splice variants (AR-Vs) in all other experiments. TGF-β inhibitor SB525334 was obtained from Sigma–Aldrich.

Knockdown analysis using siRNAs

The following double-stranded RNA 25-bp oligonucleotides were commercially generated (Life Technologies Corporation): 5’-CUUCCUGCGUUGCUAGGCCUGC-3’ (sense) and 5’-GACAGCCUGACGAAAGAAG-3’ (antisense) for Twist1. Prostate cancer cells were transfected with siRNA using Lipofectamine 2000 (Life Technologies Corporation) according to the manufacturer’s protocol.

RNA isolation, RT, and quantitative real-time PCR

RNA isolation and RT were performed as described previously (Shiota et al. 2010, 2011a, 2012b). Quantitative real-time PCR was performed using TaqMan Gene Expression Assays for Twist1 (Hs00361186_m1), full-length AR (Hs00907244_m1), AR V7 (custom-made; primer and probe sequences were described previously in Liu et al. (2014)), fibronectin (Hs01549976_m1), vimentin (Hs00185584_m1), and glyceraldehyde-3-phosphate dehydrogenase (GAPDH; Hs02758991_g1; all from Life Technologies Corporation) and TaqMan Gene Expression Master Mix (Life Technologies Corporation) on a 7900HT PCR system (Life Technologies Corporation). The transcript levels of target genes were normalized to the corresponding GAPDH transcript levels. All values represent the results of at least three independent experiments. TissueScan Prostate Cancer Tissue qPCR array III (HPRT303), which contains first-strand cDNAs prepared from 48 human prostate tissues, including both malignant and healthy controls, was purchased from OriGene Technologies, Inc. (Rockville, MD, USA).

Western blot analysis

Whole-cell extracts were prepared as described previously (Shiota et al. 2010, 2011a, 2012b). Briefly, the concentration of the prepared protein extracts was quantified using a Protein Assay (Bio-Rad Laboratories) based on the Bradford method. Aliquots (30 μg protein) were separated by 4–20% SDS–PAGE and transferred to PVDF microporous membranes (GE Healthcare Bio-Sciences Corporation, Piscataway, NJ, USA) using a semi-dry blotter. The membranes were then incubated with the primary antibodies described previously for 1 h at room temperature, followed by incubation with peroxidase-conjugated secondary antibodies for 40 min at room temperature. The bound antibodies were visualized using an ECL kit (GE Healthcare Bio-Sciences Corporation), and images were obtained using an image analyzer (Ez-Capture MG, ATTO, Tokyo, Japan).

Cell invasion assay

Cell invasion assay was performed as described previously (Shiota et al. 2013b). Briefly, cell invasion was performed using 8-μm pore matrigel invasion chambers (BD Biosciences). Prostate cancer cells (5 × 10⁴) were deposited in the upper chamber with 500 μl of serum-free medium, and the lower compartment was filled in 500 μl of media with 10% FBS. After incubation for 24 h, non-invaded cells on the upper surface of the filter were carefully removed with a cotton swab, and cells were fixed with 100% methanol for 2 min. Invading cells on the lower side of the filter were stained with 0.5% crystal violet for 5 min, and the dye was eluted with Sorensen’s solution (30 mM sodium citrate, 0.02 M HCl and 50% ethanol) and optical density (OD) was measurement at a wavelength of 595 nm. The results are representative of at least three independent experiments.

Cytotoxicity analysis

Cytotoxicity analysis was performed as described previously (Shiota et al. 2012c). Briefly, prostate cancer cells (2.5 × 10⁵) were seeded in 96-well plates. On the following day, media was changed to CSS-media with or without 1 nM of DHT. After 72 h, the surviving cells were stained using the alamarBlue assay (TREK Diagnostic Systems, Inc., Cleveland, OH, USA) at 37 °C for 180 min. The absorbance of each well was measured using an ARVO MX plate reader (Perkin Elmer, Inc., Waltham, MA, USA). The results are representative of at least three independent experiments.

Immunohistochemistry

Immunohistochemical staining was performed as previously described (Imada et al. 2013). Briefly, the
Endocrine-Related Cancer

M Shiota et al. Crosstalk between EMT and castration resistance 22:6 892

EnVision Plus detection system (DAKO, Glostrup, Denmark), with the primary antibodies against AR (N-20; 1:100) and Twist1 (T6451 from Sigma-Aldrich; 1:200) were used. Four micrometer-thick sections from 10% formalin-fixed paraffin embedded material were deparaffinized in xylene and rehydrated with ethanol. Endogenous peroxidase activity was blocked for 30 min using methanol containing 0.3% hydrogen peroxide. Antigen retrieval was performed by microwave heating for 20 min with Target Retrieval Solution (pH 9.0; DAKO). Next, the sections were incubated at 4°C overnight with the primary antibody, followed by staining for 40 min with the secondary antibody/peroxidase-linked polymers (EnVision+; DAKO) at room temperature. The reaction products were visualized by dianibenzidine tetrahydrochloride as a chromogen. Finally, the sections were counterstained with hematoxylin.

Immunohistochemical analysis

AR nuclear expression was assessed by counting the stained nuclei from at least 1000 tumor cells, selected from the areas of greatest accumulation of positive signals (hotspots). For scoring Twist1 expression, we assessed the proportion of stained cells divided into five categories as follows: 0, completely negative; 1, 1–25%; 2, 26–50%; 3, 51–75%; 4, 76–100%. Staining intensity was divided into four categories as follows: 0, negative; 1, weak; 2, moderate; 3, strong. The proportion and intensity scores were then multiplied to obtain a total score (Chu et al. 2012).

In vivo tumor model

Xenograft experiments in mice were performed as previously described (Shiota et al. 2012b). Briefly, to obtain LNCaP xenograft tumors, LNCaP cells (5×10⁶) with 0.1 ml matrigel (BD Biosciences) were inoculated in the flank of 6- to 8-week-old male athymic nude mice. Castration was conducted when tumor volume reached more than 100 mm³. At the time when tumor volume reached to over 1000 mm³ with castration (CRPC tumors, n = 5) or without castration (naïve tumors, n = 3), xenografts were harvested and then analyzed. To examine the effect of castration and TGF-β inhibitor SB525334 on 22Rv1 tumor growth, 22Rv1 cells (3×10⁶) with 0.1 ml matrigel (BD Biosciences) were inoculated in the flank of 6- to 8-week-old male athymic nude mice. The following day, mice were then randomly divided into four groups for treatment with castration and/or SB525334.
Each experimental group consisted of eight mice. After randomization, castration was conducted and SB525334 at a dose of 200 mg/l drinking water was started to be given every day as previously shown (Laping et al. 2007) at 2 weeks after inoculation. Then, tumor size in mice was measured weekly.

Tumor volume was measured using calipers. Tumor volume was calculated using the formula \( V = \frac{A \times B^2}{2} \), where \( V \) is the volume (mm\(^3\)), and \( A \) and \( B \) is the long and short diameter of the tumor (mm) respectively. Animals were maintained and handled according to the Japanese government and institutional guidelines. The protocol was approved by the institutional committee.

**Statistical analysis**

All data were assessed using the Student’s \( t \)-test and \( \chi^2 \) test. Levels of statistical significance were set at \( P<0.05 \).

**Results**

Twist1 mediates TGF-\( \beta \)-induced expression of both full-length and splice-variant AR expression

Because TGF-\( \beta \) is a well-known EMT inducer, we examined the effect of TGF-\( \beta \) on this transition process. 22Rv1 cells are known to express both extra-long full-length and C-terminal-deleted splice-variants of AR (AR V7, also termed AR3) which are both detected by anti-AR antibody (N-20) recognizing N-terminus of AR protein and its growth is androgen sensitive (Dehm et al. 2008, Li et al. 2011). In addition, 22Rv1 cells express the receptor for TGF-\( \beta \) and respond to TGF-\( \beta \), while another representative AR-expressing prostate cancer cell line (LNCaP) is null for the TGF-\( \beta \) receptor (TGF-\( \beta \)R2). We have previously shown that Twist1 expression was induced and EMT markers were deregulated by exogenous administration of TGF-\( \beta \) in 22Rv1 cells (Shiota et al. 2012a).

22Rv1 cells were used as model AR-expressing prostate cancer cells for assessing the effects of TGF-\( \beta \) exposure. First, we examined Twist1 and AR transcript levels after TGF-\( \beta \) stimulation. As shown in Fig. 1a, Twist1 and both full-length and splice-variant transcript forms of AR were induced by TGF-\( \beta \) stimulation in a time-dependent manner. Similarly, at the protein level, the expression of Twist1 and both full-length (upper band) and splice variants of AR (lower band) were induced by exposure to TGF-\( \beta \) (Fig. 1b).

To delineate the role of the Twist1 transcription factor in AR induction by TGF-\( \beta \), the effect of Twist1 silencing on AR induction by TGF-\( \beta \) was examined. As shown in Fig. 1c, Twist1 silencing using Twist1-specific siRNA abolished the TGF-\( \beta \)-induced up-regulation of Twist1 as well as the production of both full-length and splice-variant AR transcripts. In addition, Twist1 knockdown suppressed AR expression of both full-length and splice-variant forms at the protein level (Fig. 1d).

Furthermore, to examine long-term effects of TGF-\( \beta \) exposure, we established 22Rv1/TGF derivative from parental 22Rv1 cells by incubating these cells for more than 3 months with TGF-\( \beta \). As expected, 22Rv1/TGF cells expressed more abundant Twist1 as well as both full-length and splice-variant AR proteins, accompanied by the induction of the mesenchymal makers N-cadherin, fibronectin, and vimentin. However, expression of the epithelial marker E-cadherin remained constant (Fig. 2a). Moreover, 22Rv1/TGF cells exhibited more invasive ability compared with parental 22Rv1 cells (Fig. 2b). Finally, consistent with overexpressed AR, 22Rv1/TGF cells proliferated in a castration-resistant manner (Fig. 2c).

**Figure 2**

Long-term TGF-\( \beta \)-exposure induces EMT characteristics and AR expression. (A) Whole-cell extracts from 22Rv1 and 22Rv1/TGF cells were analyzed by SDS–PAGE and western blot analysis with specified antibodies. (B) Invasion assay was conducted using 22Rv1 and 22Rv1/TGF cells. The invasive cell count of 22Rv1 cells was set as 1. Boxes, mean; bars ± s.d.; * \( P<0.05 \) (compared with 22Rv1 cells). (C) 22Rv1 and 22Rv1/TGF cells were seeded in 96-well plates. On the following day, media was changed to CSS-media with or without 1 nM of DHT. After 72 h, cell survival rates were analyzed by cytotoxicity analyses. Boxes, mean; bars ± s.d. * \( P<0.05 \) (compared with 22Rv1 cells).
Highly invasive clone shows augmented AR signaling accompanied by a castration-resistant phenotype

Based on the results of highly invasive 22Rv1/TGF cells, we attempted to delineate the crosstalk between EMT and castration resistance using a highly invasive cell model. First, we established a highly invasive 22Rv1/HI clone from parental 22Rv1 cells; 22Rv1/HI cells exerted higher invasive ability compared with parental 22Rv1 cells (Fig. 3a).

We also compared the transcript levels of Twist1 and AR between the parental cell line and the invasive clone. As shown in Fig. 3b, transcript expression of Twist1, as well as both full-length and splice variants of AR, were up-regulated in 22Rv1/HI cells compared with parental 22Rv1 cells (Fig. 3b). In addition, similar results were obtained at the protein level (Fig. 3c). Furthermore, expression of the epithelial marker E-cadherin decreased, while mesenchymal markers N-cadherin, fibronectin, and vimentin were elevated in 22Rv1/HI cells (Fig. 3c). Consistent with increased AR expression, 22Rv1/HI cells grew well even in androgen-free conditions compared with under androgen-supplemented conditions, indicating that 22Rv1/HI cells have a castration-resistant phenotype (Fig. 3d).

AR and EMT signaling is activated in castration-resistant tumors

We aimed to examine AR and EMT signaling in castration-resistant tumors. For this objective, we used LNCaP-xenograft mouse model because LNCaP cells are a well-established and almost only castration-sensitive prostate cancer model although LNCaP cells harbor mutated AR (T877A). As shown in Fig. 4a, Twist1 and both full-length and splice-variant AR transcript levels were up-regulated in CRPC tumors compared with ADT-naïve tumors. In addition, the mesenchymal markers fibronectin and vimentin were similarly elevated (Fig. 4a); similar results at the protein level were also confirmed, as shown in Fig. 4b. Intriguingly, AR expression was different between when culture in vitro and inoculated in vivo, which may be accounted for by the environmental difference (Fig. 4b). Furthermore, immunohistochemical

Figure 3
The highly invasive clone shows augmented AR signaling accompanied by a castration-resistant phenotype. (A) Invasion assay was conducted using the indicated cells. The invasive cell count of 22Rv1 was set as 1. Boxes, mean; bars±s.d.; *P<0.05 (compared with 22Rv1 cells). (B) After extraction of total RNA from the indicated cells and cDNA synthesis, qRT-PCR was conducted using the primer pairs and probes for Twist1, full-length AR, AR V7, and GAPDH. Each transcript level from non-treated cells was set as 1. Boxes, mean; bars±s.d.; *P<0.05 (compared with 22Rv1 cells).

Boxes, mean; bars±s.d.; *P<0.05 (compared with 22Rv1 cells).

(C) Whole-cell extracts from the indicated cells were analyzed by SDS–PAGE and western blot analysis with specified antibodies. (D) 22Rv1 and 22Rv1/HI cells were seeded on 96-well plates. On the following day, media was changed to CSS-media with or without 1 nM of DHT. After 72 h, cell survival rates were analyzed by cytotoxicity analyses. Boxes, mean; bars±s.d.

*P<0.05 (compared with 22Rv1 cells).
staining showed that increased Twist1 and AR expression was evident in CRPC tumors compared with ADT-naïve tumors (Fig. 4c). Moreover, the positive rate of Twist1 nuclear staining was higher in CRPC tumors (40%) compared with ADT-naïve tumors (0%). To compare the invasive ability between androgen-dependent cells and castration-resistant cells, we performed invasion assays using LNCaP cells and its castration-resistant derivative,
C4-2 cells. As shown in Fig. 4d, the invasive ability of C4-2 cells was higher than LNCaP cells.

**Twist1 and AR transcript expression in human prostate cancer tissues**

We examined Twist1 and AR expression in human prostate tissues using tissue arrays containing cDNA from nine normal prostatic tissues and 39 prostate cancer tissues, including 18 tissues with pT2 tumors and 21 tissues with pT3 tumors. The result showed that both Twist1 ($P=0.0089$) and AR ($P=0.090$) transcript expression were elevated in prostate cancer tissues compared with normal prostatic tissues (Fig. 5a), indicating the biological relevance of Twist1/AR signaling in human prostate tissues.

In addition, full-length AR transcript expression was elevated in tumors with extraprostatic extension (pT3) compared with organ-confined tumors (pT2), as shown in Fig. 5b. Similarly, splice-variant AR transcript expression was higher in extraprostatic-extension tumors compared with organ-confined tumors ($P=0.029$; Fig. 5b).

**TGF-β inhibitor suppresses Twist1 and AR expression as well as prostate cancer proliferation**

To investigate the effect of inhibiting TGF-β signal, we utilized small molecule TGF-β inhibitor SB525334. Then, the expression levels of Twist1 and AR were examined. Although Twist1 as well as both full-length AR and AR V7 expression at transcript level was induced by TGF-β, TGF-β inhibitor SB525334 abolished the inductions of Twist1 as well as both full-length AR and AR V7 transcripts (Fig. 6a). Consistently, similar result was obtained also at protein level (Fig. 6b). In addition, TGF-β inhibitor SB525334 suppressed the augmented cell proliferation by TGF-β although unaffected cell proliferation without TGF-β (Fig. 6c).

Finally, we examined the effect of TGF-β inhibitor SB525334 combined with or without castration on *in vivo* tumor growth. The result showed that TGF-β inhibitor SB525334 significantly combined with castration suppressed 22Rv1 tumor growth most effectively although castration alone marginally suppressed tumor growth (Fig. 6d). Consistently, phosphorylated Smad2/3 levels in tumors were augmented by castration alone although blunted with SB525334 treatment (Fig. 6e). On the other hand, bodyweight was constant during 4 weeks of treatment was constant among each arm, suggesting no apparent adverse effect of therapeutics even when combined (Fig. 6f).

**Discussion**

It is well known that clinically high-burden prostate tumors with evidence of invasion and multiple metastases represented by high TNM stage are more likely to become castration resistant (Cooperberg et al. 2009). It was also reported that CTC counts increased according to castration-resistant progression after suppression by ADT (Danila et al. 2011, Miyamoto et al. 2012), suggesting that CRPC may have higher metastatic potential compared with androgen-dependent prostate cancer cells by disseminating cancer cells systemically. However, it remains unclear why advanced prostate cancer with metastases more easily becomes castration resistant and *vice versa*.

Previously, we and others have shown that the EMT-inducing factor TGF-β up-regulated Twist1 transcription factor in PC-3 and 22Rv1 cells (Shah & Kakar 2011, Shiota et al. 2012a). Conversely, we have reported that Twist1 regulated AR expression in LNCaP and 22Rv1 cells (Shiota et al. 2010), suggesting that the contribution of Twist1 to castration resistance through augmented AR signaling. Therefore, we speculated that AR expression might be
induced by TGF-β stimulation via the Twist1 transcription factor. As expected, short- and long-term stimulation with TGF-β induced Twist1 and AR expression in 22Rv1 cells, accompanied by a mesenchymal phenotype as represented by increased expression of mesenchymal markers and increased invasive ability. Taken together, these findings suggest that TGF-β induces a mesenchymal phenotype and augments AR signaling through the Twist1 transcription factor thereby promoting castration resistance, which is indicative of a close link between EMT and castration resistance (Fig. 7). Consistent with our current findings, it has previously been reported that TGF-β and AR signaling mutually promoted their respective signals in PC-3 and LNCaP cells in which AR and TGF-βR2 are overexpressed (Zhu et al. 2008). However, in classical TGF-β-induced pathway activation, Smad3/4 functions as both an AR co-activator and co-repressor, suggesting a complex role for Smad3/4 pathway in regulating AR signaling (Kang et al. 2002).

Concerning the biological role of TGF-β in prostate cancer, it has been shown that signaling by bone morphogenetic proteins (BMPs), belonging to the TGF-β superfamily, play pivotal roles in bone metastasis (Ye et al. 2011), which is one of the most common and severe complications of prostate cancer. Based on the findings in this study, BMPs, like TGF-β, in bones might promote EMT as well as castration resistance in bone-metastatic prostate cancer, which is reflected in the clinical finding that prostate cancer with multiple bone metastasis frequently and rapidly becomes castration resistant (Cooperberg et al. 2009).

In this study, we examined the status of AR signaling and castration resistance using cells with high EMT characteristics, which share the same characteristics as cells in the presence of TGF-β. To develop the experimental model, we established a clone of highly invasive cells by matrigel invasion selection (Jacob et al. 1995). The selected clone (22Rv1/HI cells) exhibited mesenchymal characteristics manifested by high invasiveness as well as decreased epithelial markers and increased mesenchymal makers concurrent with increased expression of Twist1 as well as both full-length and splice-variant forms of AR. Based on augmented AR expression in 22Rv1 cells, castration resistance was promoted in 22Rv1/HI cells, suggesting that a highly invasive clone with a mesenchymal phenotype easily developed castration resistance analyses. Boxes, mean; bars ± S.D.; *P < 0.05 (compared with no treatment).

Figure 6
TGF-β inhibitor suppresses Twist1 and AR expression as well as prostate cancer proliferation. (A) 22Rv1 cells were treated with 5 ng/ml TGF-β for 24 h. (A) qRT-PCR was conducted using the primer pairs and probes for Twist1, full-length AR, AR V7, and GAPDH. Each transcript level from non-treated cells was set as 1. Boxes, mean; bars ± S.D.; *P < 0.05 (compared with no treatment). (B) Whole-cell extracts were analyzed by SDS-PAGE and western blot analysis with specific antibodies. (C) 22Rv1 cells were seeded in 96-well plates. On the following day, media was changed to serum-free media with or without 5 ng/ml TGF-β and/or 5 μM SB525334. After 48 h, cell survival rates were analyzed by cytotoxicity assays. (D) 22Rv1 cells were inoculated subcutaneously into the lateral flank of mice. The following day, mice were randomly divided into four groups, and treatment with or without castration and SB525334 was started. The sizes of primary tumors were determined every week using calipers. Tumor growth in mice xenograft is shown. Boxes, mean; bars ± S.E.M.; *P < 0.05 (compared with no treatment). (E) The extracts from randomly selected tumors analyzed by SDS-PAGE and western blot analysis with specified antibodies. (F) Body weight in mice treated with castration and/or SB525334 for 4 weeks is shown. Boxes, mean; bars ± S.E.M.
in an experimental model. Our results corroborate a previous study in which highly invasive clones from androgen-dependent prostate cancer cells expressed higher levels of AR (Hara et al. 2008).

Conversely, several studies have proposed AR overexpression in prostate cancer as a mechanism for the progression to castration resistance after androgen deprivation (Shiota et al. 2011b). As well, TGF-β1 expression was also shown to be induced by androgen deprivation in human prostatic tissues (Fuzio et al. 2012). We and others have shown that the EMT-regulating transcription factor Twist1 was induced by androgen deprivation (Shiota et al. 2012b, Sun et al. 2012). Furthermore, CRPC tumors from LNCaP-xenograft model using castrated mice showed augmented AR signaling as well as an EMT phenotype, characterized by increased expression of Twist1 as well as other mesenchymal markers. These findings indicate that the development of castration resistance occurs after androgen deprivation induced EMT (Fig. 7), which leads to more aggressive characteristics, such as high invasion and metastasis as well as possible resistance to anticancer treatment by cytotoxic agents, including taxanes, resulting in critical, terminal illness (Shiota et al. 2013a).

Recently, TGF-β was suggested to play a critical role not only in prostate tumor progression, but also prostate carcinogenesis (Franco et al. 2011). In fact, TGF-β levels in urine were elevated in prostate cancer patients compared with normal controls (Perry et al. 1997), although the same pattern was not observed with respect to serum levels (Wolff et al. 1998). In this study, we showed elevated Twist1 and AR expression, which are induced by TGF-β, in prostate cancer tissues compared with normal prostatic tissues. Consistent with this result, Twist1 was previously shown to be up-regulated in prostate cancer compared with normal prostatic tissue (Kwok et al. 2005), in addition to the well-known roles of AR in prostatic carcinogenesis. Accordingly, Twist1/AR signaling was suggested to play a critical role not only in human prostate cancer progression, but also in prostate carcinogenesis.

Accumulating evidence has recently emerged supporting the role of deregulated AR in promoting the EMT process. In androgen-dependent prostate cancer cells, AR signaling increased invasive ability by mediating metalloproteinase and TMPRSS2 activities (Lucas et al. 2014). Furthermore, activated AR stimulated β-catenin and suppressed E-cadherin gene expression in prostate cancer cells, resulted in an induction of mesenchymal-like cell morphology (Liu et al. 2008, Zhu & Kyprianou 2010).

It has recently been reported that AR splice variants dominantly regulate the expression of the mesenchymal marker N-cadherin (Cottard et al. 2013). The present study showed that CRPC tumors in which AR expression was elevated showed mesenchymal characteristics manifested by increased expression of mesenchymal markers, suggesting that CRPC tumors may have highly invasive and metastatic potential. This is supported by a recent report showing that N-cadherin is up-regulated in CRPC tissues (Tanaka et al. 2010). As shown in this study, AR expression was elevated in invasive prostate cancer, which is consistent with a previous report showing that higher levels of AR expression is correlated with extraprostatic extension, seminal vesicle invasion, and lymph-node involvement in radical prostatectomy specimens (Li et al. 2004). Collectively, the findings revealed in this study have suggested the hypothesis that an inhibition of EMT signaling induced by blocking AR signaling would lead to the eradication of compensated augmentation of AR signaling as well as castration resistance. Actually, reversed EMT signaling by TGF-β inhibitor suppressed Twist1 and AR expression as well as tumor growth combined with castration probably due to an inhibition of castration resistance. This result is consistent with the previous
reports that TGF-β inhibitor restored chemo-sensitivity to paclitaxel (Bhola et al. 2013) and radio-sensitivity in breast cancer (Bouquet et al. 2011). This study has successfully shown that TGF-β receptor inhibitor SB525334 could suppress tumor growth of 22Rv1 cells specifically in combination with castration although SB52334 alone did not. This result indicates that TGF-β-targeting therapy may be a favorable combination with ADT in prostate cancer by inhibiting EMT as well as the development of castration resistance as shown in Fig. 7.

In conclusion, this study revealed that TGF-β induced mesenchymal conversion by increasing Twist1/AR signaling, and that clonal selection contributes to an EMT phenotype as well as augmented AR signaling, leading to castration resistance. Furthermore, we report that augmented Twist1/AR signaling in CRPC promotes EMT. Taken together, these results revealed the molecular mechanism of close mutual and functional crosstalk between EMT and castration resistance mediated by Twist1/AR signaling, which may play a crucial role in prostate carcinogenesis and progression. Actually, dual inhibition of EMT and AR signaling coordinately suppressed tumor growth through coordinate inhibition of mechanisms for EMT and castration resistance. Thus, the identification of the crosstalk between EMT and castration resistance by Twist1/AR signaling offers the potential to develop novel strategies for overcoming progression and castration resistance in prostate cancer. The biological findings in this study also suggest that AR signaling in EMT during embryonic prostate genesis might be required and androgen deprivation might cause prostate cancer cells to migrate to distant locations to survive.

Declaration of interest
The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

 Funding
This work was supported by Kakenhi grants (25462483, 25462484 and 26861273) from the Ministry of Education, Culture, Sports, Science, and Technology of Japan (MEXT), Japan; a Medical Research Promotion Grant from Takeda Science Foundation, Japan; and a Research Promotion Grant from the Uehara Memorial Foundation, Japan.

Acknowledgements
We are grateful to Dr Martin Gleave (Vancouver Prostate Centre, Vancouver, BC, Canada) for providing the C4-2 cells. We would like to thank Edanz Group Japan for editorial assistance, and Ms Noriko Hakoda and Ms Eriko Gunshina for technical assistance.

References
Endocrine-Related Cancer


M Shiota et al. Crosstalk between EMT and castration resistance

Endocrine-Related Cancer 18 507–514. (doi:10.1530/ERC-11-0017)


Received in final form 24 August 2015
Accepted 26 August 2015
Made available online as an Accepted Preprint
26 August 2015