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SIX1 maintains tumor basal cells via transforming growth factor-β pathway and associates with poor prognosis in esophageal cancer

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Esophageal squamous cell carcinoma (ESCC) is one of the most common malignant tumors in Eastern Asia with extremely poor prognosis due to late presentation and rapid progression.1,2 Neoadjuvant chemoradiotherapy (CRT) followed by surgery is the standard therapy in Western countries, whereas neoadjuvant chemotherapy followed by surgery and definitive CRT are the standard therapies in Japan.2 Although improvement in both surgical techniques and neoadjuvant chemotherapy has been achieved, the 5-year survival rate of locally advanced tumors was, at best, still 55%. Therefore, elucidation of mechanisms of the malignancy is eagerly awaited. Epithelial-mesenchymal transition (EMT) by transforming growth factor-β (TGF-β) has been reported to have critical biological roles for cancer cell stemness, whereas little is known about it in ESCC. In the current study, a transcriptional factor SIX1 was found to be aberrantly expressed in ESCCs. SIX1 cDNA transfection induced overexpression of transforming growth factors (TGFβ1 and TGFβ2) and its receptor (TGFβR2). Cell invasion was reduced by SIX1 knockdown and was increased in stable SIX1-transfectants. Furthermore, the SIX1-transfectants highly expressed tumor basal cell markers such as NGFR, SOX2, ALDH1A1, and PDPN. Although mock-transfectants had only a 20% PDPN-high population, SIX1-transfectants had 60–70%. In two sets of 42 and 85 ESCC patients receiving surgery alone or neoadjuvant chemoradiotherapy followed by surgery, the cases with high SIX1 mRNA and protein expression level significantly showed a poor prognosis compared with those with low levels. These SIX1 high cases also expressed the above basal cell markers, but suppressed the differentiation markers. Finally, TGF-β signaling blockade suppressed ESCC cell growth in association with the reduction of PDPN-positive tumor basal cell population. The present results suggest that SIX1 accelerates self-renewal of tumor basal cells, resulting in a poor prognosis for ESCC patients.

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Particularly, SIX1 has reported to be overexpressed and associated with poor prognosis in various human cancers.\(^{(13-18)}\) In breast cancer, SIX1 induces EMT- and stem cell-like phenotypes through the upregulation of transforming growth factor β (TGF-β) signaling.\(^{(18-20)}\) In ESCC, we revealed that SIX1 also induces EMT, inhibits cell differentiation, and promotes self-renewal of cancer stem cells via TGF-β signaling, and that its inhibition causes the reduction of stem cell population and induction of cell death. Therefore, the SIX1-regulated TGF-β signaling pathway has a potential to be a therapeutic target in ESCC.

Materials and Methods

**Tissue samples of ESCC and normal esophagus.** Both esophageal cancer tissues and their matched noncancerous tissues were obtained with written informed consent from locally advanced ESCC patients who underwent esophagectomy at the National Cancer Center Hospital (Tokyo, Japan) and Hiroshima University Hospital (Hiroshima, Japan), and biopsy samples of locally advanced ESCC before treatment were provided by the National Cancer Center Hospital East (Kashiwa, Japan) after obtaining written informed consent from each patient and approval by the institutional review boards.

**Cell culture.** All ESCC-derived cell lines, were cultured in RPMI-1640 (Wako Pure Chemical Industries, Osaka, Japan) supplemented with 10% fetal bovine serum, penicillin-streptomycin at 37°C, with 5% CO\(_2\) in 95% humidified air.

**Reverse Transcription-PCR and quantitative real-time PCR.** Ten micrograms of cRNA from 1 to 5 µg total RNA was prepared from the esophageal cancer cell lines and the surgical specimens and esophageal epithelial cells of mice were lysed by ISOGEN lysis buffer (Nippon Gene, Toyama, Japan), extracted with chloroform, and precipitated with a glycerogen carrier in isopropanol. The mRNA was amplified by an efficient method of high-fidelity mRNA amplification developed by us, called TALPAT (T7RNA polymerase promoter-attached, adaptor ligation mediated, and PCR amplification followed by in vitro T7-transcription).

**Proteins.** The value of 1/2N (N: the number of PCR cycles corresponding to the onset of the linear amplification of each gene product) was calculated as a relative mRNA expression level of each gene normalized to ACTB. Primers used for the study are listed in Supplementary Table S1.

**Plasmid construct and transfection.** The pCMV6-XL5 containing SIX1 cDNA was purchased from OriGene Technologies (Rockville, MD, USA) and integrated into pcDNA3.1 vector (Invitrogen). 2 × 10\(^3\) cells were inoculated, and then transfected with either pcDNA3.1-SIX1, or no insert of pcDNA3.1-mock using Lipofectamine 2000 reagents according to the manufacturer’s protocol (Invitrogen). The cells were selected with 0.5 mg/mL G418 (Invitrogen) from 2 days post-transfection, and simultaneously harvested at 2 days after transfection for RT-PCR analysis. Cells were also subjected to limiting dilution in a 96-well plate for obtaining colonies. SIX1 mRNA expression levels of the clones were examined by quantitative RT-PCR.

**Immunohistochemical analysis.** Specimens fixed in formalin and embedded in paraffin were cut into 4-µm sections, subsequently dewaxed, and dehydrated. Sections were blocked for DAKO protein block (DAKO, Carpinteria, CA, USA), and stained with primary antibodies against Six1 (1:100, Atlas antibodies, Stockholm, Sweden), and PDPN (1:50, Acris Antibodies GmbH, Herford, Germany) at 4°C overnight, followed by incubation with EnVision + Dual Link System-HRP (DAKO). Subsequently, these sections were exposed by DAB for 5 min. The tissues were counterstained with hematoxylin and then mounted.

**Immunofluorescence staining.** Cells were cultured on glass chamber slides, and then fixed with 4% paraformaldehyde, permeabilized with –20°C methanol and 0.5% Triton X-100/PBS, and blocked with 0.1M NH\(_4\)Cl, 10% fetal bovine serum and 2% bovine serum albumin in phosphate -buffered saline (PBS). Cells were incubated with primary antibody for PDPN (1:50, Acris Antibodies GmbH), and then incubated with Alexa488-conjugated anti-mouse IgG antibody (1:800, Invitrogen) and stained with DAPI.

**siRNA transfection.** Purchased siRNA (ID: s227324, Ambion, Austin, TX, USA) were transfected to ESCC cells using DharmFECT (Thermo Fisher Scientific, Waltham, MA, USA) following the procedure recommended by the manufacturer. Quantitative RT-PCR and Matrigel invasion assay were carried out after siRNA treatment of ESCC cells.

**Matrigel invasion assay.** Invasion abilities of ESCC cells in vitro were measured by BD BioCoat Matrigel Invasion Chamber (BD Biosciences, San Jose, CA, USA) according to the manufacturer’s protocol. The cells were trypsinized and transferred into wells at 24 h after siRNA transfection. After incubation for 24 h, the cells that passed through the filter into the lower wells were fixed, stained, and counted.

**Flow cytometry analysis.** Cells were harvested, and incubated with anti-PDPN antibody (1:100, Abcam, Cambridge, UK) or isotype control mouse IgG1 for 30 min on ice followed by PBS washing. Anti-mouse IgG-Alexa488 (1:800; Invitrogen) was used as a secondary antibody. Dead cells were labeled with propidium iodide and were excluded from the analysis. Flow cytometry analysis was performed using FACSCalibur (BD Biosciences).

**Western blot.** Cells were lysed in Laemmli Sample buffer (Bio-Rad, Hercules, CA, USA) containing DTT and 1% protease inhibitor cocktail. Nuclear extracts at 24 h after TGF-β (R&D Systems, Minneapolis, MN, USA) treatment or at 48 h after TGF-β receptor inhibitor (A-83-01, Wako, Tokyo, Japan) treatment were prepared by using NE-PER Nuclear and Cytoplasmic Extraction Reagents (Thermo Fisher Scientific). The samples were separated using 12% SDS-PAGE. Proteins were
transferred to polyvinylidene fluoride (PVDF) membrane and blocked with 5% membrane blocking agent (GE Healthcare, Buckinghamshire, UK) in PBS, and probed with anti-SIX1 antibody (1:250, Acris Antibodies GmbH, Herford, Germany) or anti-phospho-smad2/3 antibody (1:500, Cell Signaling Technology, Danver, MA, USA) at 4°C overnight, anti-α tubulin antibody (1:1000; Santa Cruz, Dallas, TX, USA) at room temperature for 1 h or anti-β actin antibody (1:500; Cell Signaling Technology) at room temperature for 2 h, then washed and incubated with HRP-conjugated anti-rabbit immunoglobulin (DAKO) at room temperature for 2 h. Immunoreactive protein bands were identified with Pierce ECL Plus Western Blotting Substrate (Thermo Fisher Scientific).

Treatment of TGF-β receptor inhibitor. Cells were seeded at a density of 5 × 10⁵ cells per 100 mm dish with RPMI-1640 containing 10% fetal bovine serum (FBS). The following day, cells were treated with 1 μM or 10 μM A-83-01 and the medium was changed every 2 days until 7 days post-treatment. Cells were trypsinized, counted the viable cells, and prepared for flow cytometry and RT-PCR.

Animal experiments. SIX1-transfectants were transplanted into scid/scid mice by subcutaneous injection of 5 × 10⁶, 1 × 10⁷, or 2 × 10⁷ cells under anesthesia. Briefly, the cells were resuspended in a 6:4 mixture of medium and Matrigel (BD Biosciences). Tumor growth of total six mice was observed for 7 weeks. All animal studies were approved by the Animal Experiments Committee at the National Cancer Center Research Institute.

Statistical analysis. Clinical samples were classified into two groups for each analysis: samples in which SIX1 expression was higher than the mean (SIX1 "high"), and lower than the mean (SIX1 “low”). Each dataset was analyzed separately and P-values were calculated by log-rank analysis. The accepted level of significance was P < 0.05.

Results

Expression of SIX1 in esophageal squamous cell carcinomas (ESCCs). We first investigated SIX1 and PDPN mRNA expressions in eight ESCC cell lines (TE1, TE3, TE5, TE6, TE8, TE10, T.Tn, and KYSE510) and normal esophageal epithelium that was divided into basal, epibasal, and differentiated cell layers by laser-captured microdissection. SIX1 mRNA was detected in ESCC cell lines by 30 cycles of PCR, while

Fig. 1. Selective expression of SIX1 in esophageal squamous cell carcinoma (ESCC). (a) Semiquantitative RT-PCR analyses of SIX1 and PDPN in eight ESCC cell lines (30 PCR cycles for SIX1 and PDPN) and three layers (Differentiated, Epibasal, and Basal cell layer) of normal esophageal epithelium that was divided into basal, epibasal, and differentiated cell layers by laser-captured microdissection. SIX1 mRNA was detected in ESCC cell lines by 30 cycles of PCR, while...
that was detected in normal basal cell layer only by more than 50 cycles. Accordingly, we concluded that SIX1 was activated in most of the ESCC cell lines, but suppressed in normal epithelium (Fig. 1a). Correlation in mRNA expression between SIX1 and PDPN, which is a basal and ductal cell marker, was observed in ESCC cell lines except TE10.

Fig. 2. Expression of SIX1 in normal esophagus, hyperplasia, early esophageal squamous cell carcinoma (ESCC) and advanced ESCC. Representative images of immunohistochemistry for SIX1 in normal esophagus (left top), hyperplasia (right top), early cancer (left bottom), and invasive front in advanced ESCCs (right bottom). Section is counterstained with hematoxylin. SC, squamous cell. Scale bars represent 500 μm and 200 μm.

Fig. 3. SIX1 regulated genes related to epithelial-mesenchymal transition (EMT) by transforming growth factor-β (TGF-β) pathway. (a) Semi-quantitative RT-PCR of SIX1, an epithelial marker (CDH1), a mesenchymal marker (VIM), TGF-β related genes (TGFB2 and TGFBI), and their receptors (TGFBR1 and TGFBR2) in TE1 cells transiently transfected with human SIX1 cDNA or mock vector. Total RNA is recovered from cells at 48 h after transfection. A size marker lane is cropped from a photograph. (b) Matrigel invasion assay of TE3 cells transiently knockdown by SIX1 siRNA (upper right). Cells are transferred into matrigel at 24 h after transfection of SIX1 or control siRNA. Migrated cells are counted at 24 h after transfer. Data are mean ± SD from three independent experiments. Data of quantitative RT-PCR (upper left) and Western blotting (lower) of SIX1 are also shown. (c) Quantitative RT-PCR analysis of SIX1 in SIX1-stable transfectants (TE6-SIX1-13 and TE6-SIX1-17) and mock-transfectants (TE6-Mock). Data are mean ± SD from three independent experiments. * P < 0.05, *** P < 0.005. (d) Semi-quantitative RT-PCR of SIX1 and TGF-β signal-related genes (TGFB2, TGFBI, TGFBR1, TGFBR2, SOX2, and SOX4) in the two SIX1-transfectants and mock-transfectants. Lanes of a size marker, positive control (left of TE6-Mock), and another unstable clone (right) are cropped from a photograph. Photographs of five full uncut gels were shown in Fig. S3.
Next, we analyzed the mRNA expression of SIX1 in 60 pairs of primary ESCCs and its corresponding normal portions by real-time RT-PCR, and found more than 90% of ESCCs showed aberrant expression of SIX1 (Fig. 1b, red lines). We also investigated the relationship between the SIX1 mRNA level and the status of lymph node metastasis in 42 surgically resected specimens of locally advanced ESCC (stage II and III). The result showed that SIX1 mRNA expression was significantly higher in 30 cases that had more than five metastatic lymph nodes than in 12 cases with no metastatic lymph nodes (Fig. 1c). Accordingly, the high SIX1 expression was significantly correlated with the poor prognosis of ESCC patients received by surgery alone (Fig. 1d).

We also performed immunohistochemical analyses to evaluate SIX1 protein expression in normal mucosa, hyperplasia, and cancer. Consistent with the above mRNA expression analyses, SIX1 was expressed neither in normal stratified squamous cell layer nor hyperplasia, but was expressed in the normal duct and tumor basal cells of an early ESCC (Fig. 2). Of particular note, SIX1 was positively stained at basal layers or the invasive front in advanced ESCCs (Fig. 2), indicating its involvement in invasion and cell motility. Based on these results, we focused on the impact of SIX1 expression on epithelial-mesenchymal transition (EMT) and on tumor basal cell or cancer stem cell phenotype, since SIX1 has been reported to be an EMT inducer in breast cancer.\(^{19, 20}\)

SIX1 induces TGF-β signal-related genes and undifferentiated basal cell phenotype in ESCC cells. To investigate the biological role of SIX1 in ESCCs, we performed transient transfection of SIX1 cDNA to TE1 cells. RT-PCR analysis revealed that overexpression of SIX1 led to upregulation of a mesenchymal marker, vimentin (VIM), and downregulation of an epithelial marker, E-cadherin (CDH1) (Fig. 3a). Interestingly, a series of the TGF-β-related genes (TGFBI and TGFB2) and their receptor genes (TGFBR1 and 2) were highly expressed accompanying SIX1 overexpression (Fig. 3a). Furthermore, the invasive ability of TE3 cells was significantly reduced by siRNA-based knockdown of SIX1 mRNA and protein (Fig. 3b). These results suggest that SIX1 promotes tumor invasion through EMT induction via TGF-β signaling in ESCC.

Next, we chose TE6 cell line with low invasion ability (Fig. S1) and established two clones stably expressing SIX1 (TE6-SIX1-13 and TE6-SIX1-17) by limiting dilution (Fig. 3c). Consistent with transient transfection of SIX1 cDNA to TE1 with a quit low SIX1 expression (Fig. 3a) and with that of SIX1 siRNA to TE3 with a significant SIX1 expression...
(Fig. S2), both TE6-SIX1-13 and TE6-SIX1-17 transfectants highly expressed TGF-β signal-related genes (TGF-β ligands, their receptors and downstream transcription factors SOXs) compared to the empty vector-transfected mixed clones, termed TE6-Mock (Fig. 3d). Lanes of a size marker, positive control (left of TE6-Mock), and another unstable clone (right) are cropped from a photograph. Photographs of five full uncut gels were shown in Fig. S3. We also confirmed no difference in their expression levels between the parental TE6 cell line and the TE6-Mock (Fig. S4). Since the CDH1 induction and VIM reduction were shown by transient SIX1 cDNA transfection (Fig. 3a), it should be noted that the reduction of CDH1 mRNA and the induction of an EMT marker (VIM) and five EMT regulators (SNAIL, ZEB1, ZEB2, TWIST1, and TWIST2) by SIX1 were not observed in the two SIX1-transfectants (Fig. S5). These data suggested that a main role of SIX1 in ESCC is the induction of TGF-β signal-related genes.

Furthermore, these two cell lines also highly expressed many markers for undifferentiated esophageal epithelial cells (i.e., basal and epibasal cells) such as NGFR, SOX2, TP63, PDPN, PTPRZ1, and LGR6 (Fig. 4a,b). Lanes of a size marker, positive control (left of TE6-Mock), and another unstable clone (right) are cropped from a photograph. Photographs of four full uncut gels were shown in Fig. S6. In accordance with a result of SIX1 knock down (Fig. 3b), both SIX1-transfectant showed higher invasive abilities than that of mock-transfectants (Fig. 4c). To explore the relationship of SIX1 and cancer stem cells, we selected PDPN from genes selectively-expressed in undifferentiated esophageal epithelial cells, since it has been reported that PDPN is a cancer stem cell marker of squamous cell carcinoma.(21,22) Flow cytometry analysis showed both of the SIX1-transfectants contained a high PDPN-positive fraction (66.7% and 59.2%, respectively) compared to that of TE6-Mock (20.7%) (Fig. 4d). We also assessed the tumorigenicity of mock- and SIX1-transfectants in immunodeficient mice. As a result, only the mouse transplanted TE6-SIX1-17 cells, which stably over-expressed SIX1 by multiple passages, developed a massive tumor (data not shown). Furthermore,

Fig. 5. Predominant expression of SIX1 in locally advanced esophageal squamous cell carcinoma (ESCC) patients with high expression of basal cell markers. (a) Immunohistochemistry of PDPN and SIX1 in serial sections obtained from two ESCCs. (b) Quantitative RT-PCR of SIX1, basal cell markers (ALDH1A1, PDPN, and SOX2), and differentiated cell markers (KRT4, FLG, SCEL, and SBSN) in 85 biopsy samples from locally advanced ESCC patients before definitive CRT. H&I: high (40 cases) and intermediate (25 cases) in SIX1 mRNA level, L: low (20 cases) in SIX1 mRNA level. Data are mean ± SD from three independent experiments. * P < 0.05.
histopathological analysis revealed this tumor tissue to be composed of PDPN-expressed cells and showed poorly differentiated histology (Fig. 4e). These results suggest that SIX1 enhances tumorigenicity and invasiveness and maintains or increases PDPN-positive cancer stem cells.

**Correlation between expression of SIX1 and tumor basal cell markers in poor prognostic ESCC patients.** We investigated colocalization of PDPN and SIX1 in tumor basal cells by serial section. In case A, both SIX1 and PDPN are diffusely stained, consistent with xenografted tumors of poorly-differentiated transfectant TE6-SIX1-17 (Figs 4e, 5a). In case B, they are colocalized at the peripheral zone where the tumor basal cells existed in the well-differentiated type of ESCCs, consistent with xenografted tumors of well-differentiated cell line KYSE510 (Figs 5a and S7). We further examined the correlation between mRNA expression of SIX1 and that of basal cell markers or differentiated markers from 85 locally advanced ESCC patients. In the SIX1 high and intermediate cases (40 and 25 cases, respectively), all basal cell markers (PDPN, ALDH1A1, and SOX2) were highly expressed compared with the SIX1 low cases (20 cases) (Fig. 5b). In contrast, well-known differentiation markers of squamous cells (KRT4, FLG, SEL, and SBSN) were significantly suppressed in the SIX1 high cases (Fig. 5b). These results also support the notion that SIX1 promotes cancer stem cell self-renewal and suppresses differentiation. Although transient transfection of SIX1 cDNA or siRNA did not alter PDPN expression (data not shown), these results indicate that SIX1 cannot directly induce PDPN expression, but can accelerate self-renewal of PDPN-positive tumor basal cells both *in vitro* (Fig. 4d) and *in vivo* (Fig. 4e).

To further investigate the correlation between SIX1 and PDPN in ESCC patients received by chemoradiotherapy followed by surgery, immunohistochemical analyses of some normal tissues and 85 ESCCs were performed. Although PDPN mRNA was detected in both the basal and epibasal cell layers (Figs 1a, 4a), PDPN protein was stained only at the basal cells in normal esophagus (Fig. 6a). Therefore, the expression of PDPN is independent from that of SIX1 in the normal epithelium. In primary ESCCs, the PDPN distribution differed among cases (Fig. 6a). Positive type 1 case was diffusely and strongly stained by anti-PDPN antibody. In positive type 2 case, PDPN staining was not strong but diffuse. Although the staining appeared weak in the positive type 3 case because of abundant stroma, almost all the cancer cells were stained. Positive types 1, 2, and 3 showed poorly-differentiated histology and were determined as totally positive, whereas positive type 4 case showed a well-differentiated histology and was stained only at the periphery of the tumor nest. Notably, PDPN-negative cases (43/85, 51%) or positive type 4 cases (26/85, 30%) showed a significantly better prognosis than those with positive types 1–3 cases (16/85, 19%) (Fig. 6b).

**Blockade of TGF-β signaling diminishes PDPN-positive cancer stem cells.** Finally, we tried blocking of TGF-β signaling to examine whether self-renewal of ESCC cells is dependent on

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**Fig. 6.** PDPN co-localized with SIX1 is a poor prognostic factor in esophageal squamous cell carcinoma (ESCC). (a) Representative patterns of immunohistochemical staining of PDPN in normal esophagus and primary ESCCs. Section is counterstained with hematoxylin. (b) Overall survival of 85 ESCC patients classified by PDPN staining patterns. P1-3: 16 cases with three positive staining patterns (positive 1-3), N+P4: 69 cases with a positive staining pattern, positive 4 (*n* = 26) or negative (*n* = 43). *P*-values are calculated by log-rank test.

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this signal pathway. The PDPN-positive cell population in 8 ESCC cell lines (TE1, TE3, TE5, TE6, TE8, TE10, T.Tn, and KYSE510) was 0.1, 85.3, 24.3, 3.4, 90.2, 1.0, 88.3, and 25.8%, respectively. After exposure to small molecular inhibitor of TGF-β receptor A-83-01(23) for 7 days, the relative viability was significantly decreased in all of the four ESCC cell lines (TE3, TE8, T.Tn, and KYSE510) harboring a high PDPN-positive cell population (Fig. 7a). In TE3 and KYSE510 highly sensitive to A-83-01, its PDPN-positive cell population was significantly reduced by A-83-01(Fig. 7b). Conversely, TGF-β treatment increased PDPN-positive cell population in TE3 and KYSE510 (Fig. S8).

The status of PDPN overexpression in two transfectants, TE6-SIX1-13 and TE6-SIX1-17, was examined by Western blotting (Fig. S9). Unfortunately, PDPN expression in TE6-SIX1-13 was decreased by multiple passages for a year. Therefore, we used only TE6-SIX1-17 in these experiments. We first showed that the phospho-Smad2/3 level increases more in TE6-SIX1-17 than in TE6-Mock after TGF-β treatment in a dose dependent manner, suggesting that TGF-β signal is activated by SIX1 (Fig. 7c, upper), and also confirmed that the phosphorylation of Smad2/3 was inhibited by A-83-01 (Fig. 7c, lower). Accordingly, the relative viability was significantly low in TE6-SIX1-17 compared with TE6-Mock (Fig. 7d). PDPN-positive cell population was also reduced in TE6-SIX1-17 but not in TE6-Mock. Representative FACS data were shown (Fig. 7e).

Discussion

The Six family of homeodomain transcription factors plays an important role in early embryogenesis(9) and normal development.(10–12) Among this family, SIX1 has been reported to express aberrantly in various types of tumors including hepatocellular carcinoma,(13) cervical cancer,(14) ovarian cancer,(15) colorectal cancer,(16) and breast cancer.(18) SIX1 has also been reported as being responsible for tumor progression, invasion or metastasis in some cancers such as hepatocellular carcinoma,(24) rhabomyosarcoma,(25) and breast cancer.(18) In infiltrating ductal breast carcinomas, the aberrant expression of SIX1 was caused predominantly by gene amplification.(26) Despite the strong relation between SIX expression and cancer progression that has been reported, detailed molecular functions of the SIX1 as an oncogene are at the beginning of understanding. For instance, CCNA1 has been reported to be a downstream effector of SIX.(27) EZR has been shown to be a target of SIX1 and to activate several oncogenes.(25) SIX1 inhibits TRAIL-mediated apoptosis in ovarian cancer, (15) and
induces EMT through ZEB1 activation and miR200 repression in colorectal cancer.\(^{16}\) In breast cancer, Mcalilizzi et al. and Farabaugh et al. have reported that SIX1 also mediates EMT and induces cancer stem cell phenotypes through TGF-\(\beta\) signaling.\(^{19,20}\) Another study has reported that SIX1 switches TGF-\(\beta\) signaling from tumor suppressive to tumor promoting by regulating miR106b-25 and Smad7.\(^{28}\) In ESCC, we found that SIX1 is also aberrantly expressed (Figs 1b, 2). More significantly, the cases with high SIX1 expression showed high lymph node metastasis and poor survival in surgery alone or chemoradiotherapy followed by surgery (Figs 1c,d, 6b). These findings strongly indicate that SIX1 is involved in cancer malignancy by promotion of metastasis. On the contrary, in ESCC patients who received definitive CRT, no significant difference is found, though cases with high SIX1 expression had a tendency for a worse prognosis (data not shown). This is partly because the malignant potential cannot be attributed to only one transcription factor. Many factors are reported to be associated with EMT in ESCC such as Twist1,\(^{29}\) Snail,\(^{30}\) hedgehog pathway,\(^{31}\) and FOXA1.\(^{32}\)

Transient transfection studies of SIX1 cDNA and siRNA showed that SIX1 induced EMT and invasiveness in ESCC (Fig. 3a,b), and the stable SIX1-transfectants showed high invasiveness without EMT (Figs 4c and S5). It should be noted that the reduction of CDH1 mRNA and the induction of an EMT marker (VIM) and five EMT regulators by SIX1 were not observed in the two SIX1-transfectants (Fig. S5). These data suggested that the role of SIX1 in ESCC is the induction of TGF-\(\beta\) signal-related genes but is unclear in the authentic EMT induction.

In accordance with previous findings in breast cancers, SIX1 activated TGF-\(\beta\) (Fig. 3a,d). Furthermore, we investigated whether SIX1 induces a cancer stem cell phenotype, since EMT is often accompanied by cancer stem cell properties.\(^{5}\) We first found that SIX1 induces some genes selectively expressed at the normal basal layer where esophageal tissue stem cells are thought to reside (Fig. 4a,b). Although little is known about the cancer stem cells of ESCC,\(^{6}\) PDNP has been reported to be a cancer stem cell marker of oral squamous cell carcinoma.\(^{21}\) In addition, Rahadiani et al. reported PDNP-positive ESCC cells have a tumor initiating ability.\(^{22}\) We confirmed that PDNP protein expression is selectively expressed at tumor basal cells of xenografted tumors and primary ESCCs (Figs 6a and S7). Thus, we used PDNP as a cancer stem cell marker of ESCC. Both SIX1-overexpressing stable cell lines (TE6-SIX1-13 and TE6-SIX1-17) had a higher population of PDNP-positive cells compared to that of TE6-Mock (Fig. 4d). In addition, PDNP expression was still high in the xenografted tumor of a SIX1-stably expressing ESCC cell line (Fig. 4e).

Therefore, these studies indicate that consistent SIX1 overexpression accelerated self-renewal of PDNP-positive cancer stem cells and promoted tumor progression. Co-expression between SIX1 and three basal cell markers (PDNP, ALDH1A1, and SOX2) and reverse correlation between SIX1 and four differentiation markers (KRT4, FLG, SCEL, and SBSN) in biopsy samples of locally advanced ESCC patients supported this notion (Fig. 5b).

Although TGF-\(\beta\) signaling induces EMT in various tumors,\(^{33,34}\) this mechanism is not well-known in ESCC. Recently, Natsuizaka et al. reported that immortalized esophageal epithelial cells underwent EMT through TGF-\(\beta\).\(^{35}\) Our data showed that TGF-\(\beta\) was upregulated by SIX1 (Fig. 3a,d). It is reported that the autocrine of TGF-\(\beta\) mediates tumorigenicity through SOX2/SOX4 in glioblastoma.\(^{36}\) Likewise, we found SOX2/SOX4 is upregulated as well as TGF-\(\beta\) by SIX1 transfection (Fig. 3d). In addition, treatment by A-83-01, a small-molecule inhibitor of the TGF-\(\beta\) receptor, suppressed growth of SIX1- and PDNP-expressing ESCC cells (Fig. 7d,e).

This result indicates that self-renewal of cancer stem cells of ESCC promoted by SIX1 is dependent on TGF-\(\beta\) signaling. To our knowledge, this is the first report that shows the effectiveness of the TGF-\(\beta\) receptor inhibitor for ESCC. More significantly, there is no finding about a specific inhibitor of the cancer stem cell of ESCC.

In conclusion, our study demonstrated that aberrant expression of SIX1 is correlated with metastasis and poor survival in ESCC patients. We also found that SIX1 accelerates self-renewal of cancer stem cells of ESCCs. This process is dependent on TGF-\(\beta\) signaling, and TGF-\(\beta\) receptor inhibitors may be effective in highly malignant ESCC with high SIX1 expression.

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**Disclosure Statement**

The authors declare no conflict of interest.

**References**


Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

**Fig. S1.** Relative migration ability of eight ESCC cell lines (TE8, TE3, T.Tn, KYSE510, TE1, TE5, TE6, and TE10) and an oral cancer cell line (A431) assessed by matrigel invasion assay.

**Fig. S2.** Quantitative RT-PCR of TGF-β signal-related genes (TGFβ2, TGFβ1, TGFβRI, TGFβR2, SOX2, and SOX4) in TE3 with SIX1 siRNA treatment. * P < 0.05.

**Fig. S3.** Photographs of 5 full uncult gels before cropping to make Fig. 3d were shown.

**Fig. S4.** Expression of SIX1 and TGF-β signal-related genes (TGFβ2, TGFβ1, TGFβRI, TGFβR2, and TGFβR3) in the parental TE6 cell line (TE6-Parent) and its mock-transfectants (TE6-Mock).

**Fig. S5.** Expression of an epithelial cell marker (CDH1), an EMT marker (VIM) and 5 EMT regulators (SNAI2, ZEB1, ZEB2, TWIST1, and TWIST2) in the three SIX1-transfectants (TE6-Mock, TE6-SIX1-13, and TE6-SIX1-17).

**Fig. S6.** Photographs of 4 full uncult gels before cropping to make Fig. 4b were shown.

**Fig. S7.** Representative images of HE staining and immunohistochemistry for PDPN in xenografted tumors of a well-differentiated ESCC cell line, KYSE510.

**Fig. S8.** TGF-β treatment increased PDPN-positive cell population in TE3 and KYSE510. * P < 0.05, ** P < 0.01.

**Fig. S9.** Western blots to evaluate the stability of SIX1 expression in two transfectants after multiple passages. SIX1 (left), ACTB (right).

**Table S1.** Primer sequences for RT-PCR.