HECTD1 regulates the expression of SNAIL: Implications for epithelial-mesenchymal transition

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Abstract. As a transcription factor, SNAIL plays a crucial role in embryonic development and cancer progression by mediating epithelial-mesenchymal transition (EMT); however, post-translational modifications, such as ubiquitination, which control the degradation of SNAIL have been observed to affect its functional role in EMT. In a previous study by the authors, it was demonstrated that the HECT domain E3 ubiquitin ligase 1 (HECTD1) regulated the dynamic nature of adhesive structures. In the present study, HECTD1 was observed to interact with SNAIL and regulate its stability through ubiquitination, and the knockdown of HECTD1 increased the expression levels of SNAIL. HECTD1 was discovered to contain putative nuclear localization and export signals that facilitated its translocation between the cytoplasm and nucleus, a process regulated by epidermal growth factor (EGF). Treatment with leptomycin B resulted in the nuclear retention of HECTD1, which was associated with the loss of SNAIL expression. The knockdown of HECTD1 in HeLa cells increased cell migration and induced a mesenchymal phenotype, in addition to demonstrating sustained EGF signaling, which was observed through increased phosphorylated ERK expression levels. Under hypoxic conditions, HECTD1 expression levels were decreased by microRNA (miRNA or miR)-210. Upon the observation of genetic abnormalities in the HECTD1 gene in cervical cancer specimens, it was observed that the decreased expression levels of HECTD1 were significantly associated with a poor patient survival. Thus, it was hypothesized that HECTD1 may regulate EMT through the hypoxia/hypoxia inducible factor 1α/miR-210/HECTD1/SNAIL signaling pathway and the EGF/EGF receptor/HECTD1/ERK/SNAIL signaling pathway in cervical cancer. On the whole, the data of the present study indicated that HECTD1 serves as an E3 ubiquitin ligase to mediate the stability of SNAIL proteins.

Introduction

Epithelial-mesenchymal transition (EMT) plays an important role in the metastatic process of cancer by facilitating cell migration and invasion. One of the hallmarks of EMT is to acquire mesenchymal traits through the regulation of core EMT-inducing transcriptional factors, such as increasing SNAIL/SLUG expression levels and decreasing the expression levels of E-cadherin. Several E3-ubiquitin ligases have been reported to play crucial roles in the regulation of EMT (1-3), and genetic aberrations and alterations in these ligases have been detected in numerous types of cancer (4-6).

Ubiquitination is a molecular process in which a ubiquitin protein is attached to a substrate protein; it is mediated by E1/E2/E3 multi-enzyme cascades, whereby E1 enzymes are known as the ubiquitin-activating enzymes, E2 enzymes are referred to as the ubiquitin-conjugating enzymes and E3 enzymes are the ubiquitin-protein ligases (7). Ubiquitination is one of the most important enzymatic post-translational modifications to occur that can regulate the function of proteins; it can mark proteins for degradation via the proteasome and it can alter both the cellular location and activity of proteins (8-10).

In a previous study, it was demonstrated that HECT domain E3 ubiquitin ligase 1 (Hectd1) homozygous mutant embryos exhibited numerous defects in embryonic and fetal development (11) and MEF cells isolated from Hectd1-mutant mice were observed to accelerate cell migration (12). Consistent with these observations, the present study demonstrated that
the migration of human cells in which HECTD1 was knocked down (HECTD1-KD cells) was altered, which simultaneously suppressed the degradation of SNAIL. SNAIL is a transcriptional factor. It exerts global effects on gene expression and it promotes EMT during embryonic development and cancer progression, we then hypothesized that HECTD1 plays a role in EMT via regulating SNAIL expression. Thus, the present study aimed to investigate the role that HECTD1 plays in regulating the expression of SNAIL and to elucidate the association between the HECTD1-mediated degradation of SNAIL and the EMT pathway.

Materials and methods

Cell culture and reagents. HeLa cells were obtained from the American Type Culture Collection (CCL-2) and Ca Ski cells (87020501) were purchased from the European Collection of Authenticated Cell Cultures. HeLa cells were cultured in DMEM, supplemented with 10% FBS (Sigma-Aldrich; Merck KGaA), 1,000 mg/l glucose (Sigma-Aldrich; Merck KGaA), 2 mM L-Glutamine (Sigma-Aldrich; Merck KGaA) and 1 mM sodium pyruvate (Sigma-Aldrich; Merck KGaA). Ca Ski cells were cultured in RPMI-1640 medium (Sigma-Aldrich; Merck KGaA), supplemented with 10% FBS and 2 mM L-Glutamine. All cells were maintained in a humidified atmosphere of 5% CO₂ and 37°C.

To mimic hypoxic conditions, 1x10⁵ cells were treated with 500 µM cobalt chloride (CoCl₂) for 0-60 min or 8, 16 and 24 h. For EGF treatment, 5x10⁴ HeLa cells were seeded into 24-well plates containing 12-mm round glass cover slips or on 100-mm dishes. Following 24 h of incubation at 37°C, the cells were serum-starved overnight and subsequently treated with 100 ng/ml EGF for various times.

Cell transfection. Different clones of the HECTD1 KD in HeLa or Ca Ski cells were established through the stable transfection of individual of 4 short hairpin (sh)RNAs (cat. no. TF304134; OriGene Technologies, Inc.), which consists of 4 shRNAs against HECTD1, cat. nos. F1316529, F1316530, F1316531 and F1316532. The control cells (Ctrl, NC) were stably transfected with an empty shRNA RFP Cloning Vector (scramble, pRFP-C-RS vector; cat. no. TR30014; OriGene Technologies, Inc.), which consists of 4 shRNAs against HECTD1, cat. nos. FI316529, FI316530, FI316531 and FI316532. The control cells (Ctrl, NC) were stably transfected with an empty shRNA RFP Cloning Vector (scramble, pRFP-C-RS vector; cat. no. TR30014; OriGene Technologies, Inc.). The shRNA constructs were excised with Xhol/BglII and blunt-end ligation.

miRtarBase was used to identify hypothetical target sequences for HECTD1 (http://mir tar base.mbc.nctu.edu.tw/php/search.php). microRNA (miR)-21 and miR-210 antagonirs were purchased from Ambion; Thermo Fisher Scientific, Inc. and the scrambled negative control (anti-miR-scr) was obtained from Shanghai GenePharma Co. Ltd. These antagonirs have been previously described and verified (13-15). Cells were transfected with 50 nM miR-21-210 antagonist or 25 nM anti-miR-scr using RNAiefect™ (ABM, Inc.), according to the manufacturer's protocol. The following primers were used for qPCR: U6 forward, 5’-CTCGTTTGGACGCA CA-3’ and reverse, 5’-AACGTTTCAAGATTGCCTG-3’; and HECTD1 forward, 5’-AATGAACACGGTCAACT GC-3’ and reverse, 5’-TGTGTTTGTCACACTGCA TTT-3’. The cycling conditions were as follows: 95°C for 10 min, followed by 30 cycles of (95°C for 15 sec, 60°C for 30 sec, 72°C for 40 sec), then 95°C for 60 sec. Expression levels were calculated using the 2⁻ΔΔCt method (16) and normalized to the loading control U6. All experiments were performed ≥3 times and expressed as a log₂ scale or fold change of treatment/control. Expression changes with a log₂ ratio of treatment/control >1 or <1 and P<0.05 were considered significant.

Antibodies and reagents. Anti-SNAIL (cat. no. 3879), anti-Slug (cat. no. 9585), anti-E-cadherin (cat. no. 3195), anti-N-cadherin (cat. no. 4061), anti-ERK1/2 (cat. no. 4695), anti-phospho-ERK1/2 (Thr202/Tyr204; cat. no. 4374) and anti-GAPDH (2187L) primary antibodies were purchased from Cell Signaling Technology, Inc.; the anti-HECTD1 primary antibody (cat. no. CSB-PA010273GA01HU) was obtained from Cusabio Technology LLC; the anti-ubiquitin primary antibody (cat. no. ab7780) was obtained from Abcam; and the anti-HECTD1 (M03), clone 1E10 primary antibody (cat. no. H00025831-M03) was purchased from Abnova Corp. The FITC-conjugated and Alexa Fluor 546-conjugated anti-rabbit (A-11035) or anti-mouse (A-11003) secondary antibodies were purchased from Invitrogen; Thermo Fisher Scientific, Inc. and the horseradish peroxidase (HRP)-conjugated anti-mouse (cat. no. 1706516) or anti-rabbit (cat. no. 1706515) secondary antibodies were obtained from Bio-Rad Laboratories, Inc. Anti-α-tubulin antibody was obtained from Abcam (ab52866, 1:250). Human recombinant EGF and EGF-Alexa Fluor 488 were purchased from Invitrogen; Thermo Fisher Scientific, Inc. The GFP-SNAIL plasmid (cat. no. 16225) was obtained from Addgene, Inc. and the HECTD1-HaloTag™ human ORF in pN21A clone (cat. no. FHC05410) was purchased from Promega Corp. Leptomycin B (LMB; cat. no. L2913) and ivermectin (IVE; cat. no. I8898) were purchased from Sigma-Aldrich; Merck KGaA.

Cycloheximide (CHX) chase assay and LMB or IVE treatments. Briefly, 2.5x10⁴ shRNA-transfected HeLa cells were plated on 100-mm dishes for 16 h. Following the treatment with 100 µg/ml CHX for the indicated time periods, cell pellets were harvested and lysed on ice in the supplemented RIPA buffer. Protein expression was detected by western blot analysis and quantified by densitometric analysis with ImageJ software. Three independent experiments were performed. For LMB or IVE treatments, HeLa cells were treated with or without 50 nM LMB or IVE (1 µM) for 4 h and sequentially treated with 100 ng/ml EGF.

Immunofluorescence staining. Cells were seeded into 24-well plates containing 12-mm round cover glass slips. Prior to treatment, the cells were serum-starved for 16 h. Following treatment, the cells were washed twice with PBS and fixed with 4% formaldehyde for 15 min at room temperature. The cells...
were subsequently permeabilized with 0.15% Triton-X100/PBS for 15 min at room temperature and washed twice with PBS. The cells were then blocked with 5% BSA/PBS for 1 h at room temperature and incubated at 4°C overnight with anti-HECTD1 and anti-SNAIL primary antibodies diluted 1:200 in blocking buffer. Following primary antibody incubation, the slides were washed with PBS 3 times for 15 min and were subsequently incubated with Alexa Fluor-conjugated secondary antibodies (1:500) for 1 h at room temperature. The slides were then washed 3 times with PBS and the nuclei were stained with DAPI for 3 min at room temperature. The cells were subsequently mounted with prolonged gold anti-fade mountant (Invitrogen; Thermo Fisher Scientific, Inc.) and the stained cells were visualized using the Nikon A1R confocal microscope (Nikon Corp.).

The fluorescent intensities of HECTD1 and SNAIL were quantified using NIS-Elements software (Nikon Corp.). The nuclear regions were selected with the DAPI channel and the measured intensities were subtracted from the background intensity (non-cell region) to obtain the fluorescent intensity of each protein. At least 3 independent experimental repeats were performed.

**Analysis of HECTD1 subcellular localization.** The analysis of the subcellular localization of HECTD1 was performed using two different prediction softwares: RSLpred (17) and PSORT II (18).

**Western blot analysis.** The cells were washed twice with pre-chilled PBS at 4°C and total protein was extracted on ice for 10 min using 200 µl RIPA lysis buffer, containing 10% protease inhibitor. The cells were collected into a 1.5 ml Eppendorf tube, vortexed and lysed on ice for 30 min. Subsequently, the cells were centrifuged for 15 min at 6,500 x g at 4°C and the supernatant was collected. Total protein was quantified using a protein assay (Bio-Rad Laboratories, Inc.) and 20 µg protein/lane were separated on 12% SDS-PAGE to detect ERK1/2 and phospho-ERK1/2 expression and 4% SDS-PAGE to detect HECTD1 expression. The separated proteins were subsequently transferred onto PVDF membranes and blocked with 1% milk powder. The membranes were incubated with the following primary antibodies at 4°C overnight: Anti-ERK1/2 (1:200), anti-phospho-ERK1/2 (1:1,000), anti-HECTD1 (1:200) and anti-GAPDH (1:100,000). Following primary antibody incubation, the membranes were incubated with HRP-conjugated secondary antibodies (1:5,000) for 1 h at room temperature. Protein bands were visualized using the Pierce™ ECL Plus Substrate (Pierce; Thermo Fisher Scientific, Inc.). Protein expression was quantified using ImageJ software (National Institutes of Health) and normalized to the loading control, GAPDH.

**Cell proliferation assays.** To analyze cell proliferation, the CellTiter96® AQ_{enorm}, One Solution Cell Proliferation assay (MTS; cat. no. G3582; Promega Corp.) was used according to the manufacturer's protocol. Following serum starvation overnight, a total of 5x10³ cells/well were seeded into 96-well plates with or without 100 ng/ml EGF treatment. Following incubation for 30, 48 and 72 h, 20 µl MTS solution were added to each well and the cells were incubated for 3 h at 37°C. The absorbance was measured at 490 nm using a Biotek 96-well plate reader (BioTek Instruments, Inc.). The absorbance was normalized to the absorbance at 0 h. A single experiment was performed.

**Wound healing assay.** The wound healing assay for HeLa cells was performed as previously described (12). Three independent experimental repeats were performed.

**Cell migration assay.** A total of 4x10⁵ Ca Ski or HeLa cells/ml were resuspended in serum-free DMEM and 350 µl cell suspension was plated in the upper chambers of 24-well Transwell plates (8.0 µm; cat. no. MCEP24H48; Merck KGaA). A total of 1 ml DMEM or RPMI-1640 medium supplemented with 20% FBS was plated in the lower chambers. Following incubation for 20 h at 37°C, the non-migratory cells remaining in the upper chamber were removed using cotton swabs. The migratory cells were fixed with 70% ethanol for 15 min and subsequently stained with 0.1% crystal violet for 15 min at room temperature. The stained cells were counted in four randomly selected fields using a microscope (ECLIPSE Ti2, Nikon). Three independent experimental repeats were performed.

**Co-immunoprecipitation (Co-IP).** Cell pellets were lysed with IP lysis buffer (20 mM Tris-HCl, pH 8.0, 137 mM NaCl, 1% NP40 and 2 mM EDTA supplemented with 1% protease inhibitor cocktail) on ice for 20 min. The lysate was centrifuged at 9,000 x g for 5 min at 4°C and the supernatant was collected and transferred to pre-cooled fresh tubes. The protein concentration was equilibrated with the IP lysis buffer. Subsequently, 2 µl anti-GFP GF28R antibody (Thermo Fisher Scientific, Inc.) were added per 500 µg protein sample prior to being incubated overnight at 4°C. Normal mouse IgG (1:1,000, ab188776, Abcam) was used as a negative control. The lysates were subsequently incubated with pre-washed protein G agarose beads (20 µl/500 µg protein) for 1 h at 4°C with gentle agitation. The beads were washed 3 times with IP lysis buffer and then centrifuged at 1,600 x g for 3 min at 4°C. Subsequently, the beads were heated for 5 min at 95°C in 2X Laemmli sample buffer and target proteins were detected by western blot analysis using specific antibodies as described above. Two independent experimental repeats were performed.

**Ubiquitination assay.** Following 24 h of transfection with GFP-SNAIL or GFP, HeLa cells were washed twice with PBS and incubated in serum-free medium supplemented with 1 nM MG132 or DMSO overnight at 37°C. For the endogenous ubiquitination assay, starved cells were harvested as pellets and resuspended in serum-free medium. The pellets were centrifuged 9,000 x g for 5 min at 4°C and lysed with ubiquitination lysis buffer (50 mM Tris, pH 7.5, 1 mM EDTA, 150 mM NaCl, 0.1% Triton X-100, complete protease inhibitor cocktail, 100 µM MG132 and 100 µM N-ethylmaleimide) on ice for 15 min, followed by centrifugation at 12,000 x g for 5 min at 4°C. The supernatant was collected and used to determine the total protein concentration. Equal concentrations of total protein were immunoprecipitated with GFP antibody and protein G agarose beads, and ubiquitination was subsequently detected using western blotting. Whole cell lysate, which was 5% of total protein, was used as the control. Two independent experimental repeats were performed.
Clinical specimens and immunohistochemistry. The expression levels of HECTD1 were examined in normal and cancer tissues obtained from the Human Protein Atlas (HPA; http://www.proteinatlas.org) using immunohistochemistry (IHC). Briefly, IHC was performed using anti-HECTD1 (1:50, cat. no. HPA002929; Sigma-Aldrich; Merck KGaA) and anti-SNAIL (1:500, cat. no. HPA069985; Sigma-Aldrich; Merck KGaA) primary antibodies, and the source of these tumors and the pathological analysis can be found in the online supplementary materials. Kaplan-Meier plots were generated based on the association analysis between mRNA expression levels and patient survival, and patients were subsequently divided into 2 groups based on the level of expression as the ‘Low’ or ‘High’ expression groups. Log-rank P-values are displayed. 329 cervical cancer samples from The Catalogue Of Somatic Mutations In Cancer (COSMIC) and 309 samples from The Cancer Genome Atlas (TGCA) were analyzed using whole-exome sequencing.

Statistical analysis. Statistical analysis was performed using unpaired one-way ANOVA (Tukey’s multiple comparisons test was used as a post-hoc test) or subsequent Student’s t-test using GraphPad Prism 7 software (GraphPad Software, Inc.) and data are presented as the means ± SD or SEM, as indicated in the figure legends. P < 0.05 was considered to indicate a statistically significant difference.

Results

Interaction of HECTD1 with SNAIL. It has previously been demonstrated that the degradation of SNAIL occurs through a proteasome-mediated mechanism involving several E3 ubiquitin ligases (19-21). SNAIL has been suggested to interact with HECTD1, a HECT domain E3 ubiquitin ligase involved in regulating the dynamic nature of adhesive structures in cells (11). Therefore, it was hypothesized that HECTD1 may be involved in the protein degradation of SNAIL. In this study, Co-IP assays were used to investigate whether HECTD1 physically interacted with SNAIL protein; HECTD1 was present in the immunoprecipitates of cell lysates transfected with an expression vector for GFP-SNAIL, but not in those collected following transfection with the control vector alone (Fig. 1A), although endogenous SNAIL could not be detected in a pulldown in HaloTag-HECTD1 transfected cells. These results suggest that the proteins interact with each other in vivo. To elucidate the potential role of HECTD1 in cancer, several cell lines were established in which HECTD1 was knocked down (HECTD1-KD cells) using shRNA. One of these HECTD1-KD cells established from TF304134, demonstrated markedly reduced expression levels compared with the scrambled shRNA-transfected cells (Ctrl); >90% of HECTD1 expression was knocked down in HeLa cells (Fig. S1A). Since HECTD1 is an E3 ubiquitin ligase, the HECTD1-mediated ubiquitination of SNAIL was investigated. The GFP-SNAIL vector was overexpressed in HeLa cells and ubiquitinated proteins were purified using anti-GFP antibody beads, and SNAIL expression was subsequently analyzed by western blot analysis. The ubiquitination of SNAIL was markedly increased following treatment with the proteasome inhibitor, MG132, which blocks ubiquitin-proteasome degradation (Fig. 1B). Furthermore, the HECTD1-KD cells were observed to have reduced ubiquitination levels of SNAIL (Fig. 1B), whereas cells transfected with expression pN21A plasmids containing HECTD1 (HaloTag®-HECTD1) and the GFP-SNAIL plasmid demonstrated that HECTD1 expression promoted the ubiquitination of SNAIL (Fig. 1C). Overall, these data suggest that SNAIL proteins are the target of HECTD1-mediated ubiquitination.

Mediation of SNAIL degradation by HECTD1. To identify whether HECTD1 is involved in the degradation of SNAIL, the CHX chase assay was used. Compared with the control cells (Ctrl), cells transfected with HECTD1-KD exhibited markedly decreased degradation levels of SNAIL proteins (Figs. 2A and S2), suggesting that HECTD1 may be one of the E3 ubiquitin ligases that mediates the stability of SNAIL proteins. It was subsequently hypothesized that the localization of HECTD1 within cells may affect HECTD1-mediated SNAIL degradation. Thus, to examine this hypothesis, the localization of SNAIL in HeLa Ctrl and HECTD1-KD cells was analyzed. Consistent with the results obtained by western blot analysis (Fig. 2A), it was observed that the immunoreactivity of nuclear SNAIL proteins was increased in the HECTD1-KD cells compared with the Ctrl cells (Fig. 2B and C). In contrast to the localization of HECTD1 (Fig. 3A), SNAIL expression was found to be constitutive and dependent on serum/growth factors in HeLa cells (Fig. 2B). Compared with serum starvation (EGF), the immunoreactivity of nuclear SNAIL protein was increased following the addition of EGF (Fig. 2B and D); however, SNAIL was predominantly expressed in the nucleus of the HECTD1-KD cells, regardless of the treatment condition. These results strongly suggest that HECTD1 may play an important role in controlling the abundance of SNAIL present in the nucleus.

Shuttling of HECTD1 between the nucleus and cytoplasm requires Exportin 1 (XPO1/CRM1)-mediated nuclear export. HECTD1 contains 8 putative nuclear localization sequences (NLS) and 4 nuclear export signals (NES; Fig. S3A and B). Through using two localization prediction software, it was discovered that HECTD1 expression was localized within the nucleus (Fig. S3C). Consistent with this finding, endogenous HECTD1 was also found to be localized in the nucleus following serum deprivation, despite its otherwise cytoplasmic localization (Fig. 3A and B), which is similar to FBXL5 (19), but unlike many other types of SNAIL1 E3 ubiquitin ligases, which are localized in the cytosol (21). Notably, EGF treatment stimulated the export of HECTD1 to the cytosol (Fig. 3C and D), indicating that HECTD1 may shuttle back and forth between nucleus and cytoplasm. No changes were observed in the intensity of HECTD1 immunoreactivity during the 4-h period (Fig. 3A and B).

It has been demonstrated that XPO1/CRM1 mediates the nuclear export of numerous types of protein (22), LMB, a well-known natural inhibitor of XPO1/CRM1, has been observed to reduce nuclear export (23). The treatment of HeLa cells with LMB resulted in the accumulation of HECTD1 in the nucleus (Fig. 3C and D), suggesting that HECTD1 may be actively exported from the nucleus to the cytosol. To investigate the location of HECTD1-mediated SNAIL degradation by ubiquitination, the nuclear export or import of HECTD1 was blocked by LMB or IVE (which is a specific inhibitor of importin α/β-mediated nuclear import),
respectively, and the nuclear signals and expression levels of SNAIL were determined by fluorescence intensity. LMB not only increased the nuclear signal of HECTD1, but also that of SNAIL (Fig. 3E and F); however, it was suggested that the nuclear localization of SNAIL was independent of XPO1/CRM1 in HeLa cells. The total expression levels of SNAIL were unaltered (Fig. 3G), indicating that LMB may block the nuclear export of both proteins, but the degradation of SNAIL does not occur in the nucleus. IVE treatment blocked the nuclear import of both proteins (Fig. 3E and F) and decreased the total SNAIL expression levels by 30% (Fig. 3G). Overall, these results suggest that HECTD1-mediated SNAIL degradation occurs in the cytoplasm, but not in the nucleus.

Knockdown of HECTD1 potentiates EMT. Alterations in cellular adhesion, migration, invasion and morphology are essential for EMT. The knockdown of HECTD1 induced a mesenchymal appearance in the HeLa cells (Fig. 4A). The Ctrl HeLa cells displayed a ‘cobblestone (cubed)’, epithelial-like phenotype (24), whereas the HECTD1-KD cells acquired a spindle-like, elongated phenotype, which is typical of mesenchymal cells, suggesting that the knockdown of HECTD1 may induce changes in cell morphology similar to EMT processes.

MEF cells obtained from Hectd1-homozygous mutant (Hectd1<sup>R/R</sup>) embryos exhibited an accelerated cell spreading/migratory phenotype (11). Similarly, the wound healing assays demonstrated that closure of the wound occurred more rapidly in the HECTD1-KD compared with the Ctrl cells (Fig. 4B); furthermore, in the Transwell assay, the number of migrated cells was higher in KD cells as compared to the Ctrl cells (Fig. 4C). However, the knockdown of HECTD1 in the HeLa cells did not significantly modify the proliferation rate.
of the cells (Fig. S1B). Thus, the downregulation of HECTD1 expression levels may be strongly associated with abnormal cell migration and invasion, but not with proliferation.

In addition, the alteration in the expression levels of specific transcription factors, such as SNAIL and SLUG, are also typical features of EMT (20). It has been reported
that the EGF-receptor (EGFR) is overexpressed in cervical
cancer (25), and SLUG/SNAIL are downstream mediators
of EGFR-stimulated re-epithelization (26). Thus, the study
investigated whether the protein expression levels of several
important factors in EGF-mediated EMT were associated with
the knockdown of HECTD1 expression. The Ctrl HeLa cells
expressed low levels of SNAIL, whereas the HECTD1-KD
cells demonstrated high expression levels of SNAIL
(Figs. 4D and S4A). Similar results were found for SLUG.
The adhesion molecule, E-cadherin, is considered to be an
important signaling marker for EMT (27); reduced E-cadherin
expression levels were observed in the HECTD1-KD cells,

Figure 3. HECTD1 translocates between the nucleus and cytoplasm. (A) HECTD1 shuttles between the nucleus and cytoplasm with or without EGF treatment.
The subcellular localization of HECTD1 was analyzed using fluorescence microscopy. HeLa cells were treated with or without 100 ng/ml EGF for 6 min and
immunostained with anti-HECTD1 antibody. The nucleus was stained with DAPI. The arrow-lines indicate the subcellular localizations of SNAIL, measured
as the fluorescent intensity in individual cells. (B) The export of HECTD1 from the nucleus is sensitive to LMB treatment. HeLa cells were treated with
or without 50 nM LMB for 4 h and sequentially treated with 100 ng/ml EGF. Cells were stained with anti-HECTD1 antibody and the fluorescent intensity
demonstrates HECTD1 localization. Scale bar, 10 μm. (C and D) Intensity of HECTD1 nuclear signals and whole cells were analyzed and semi-quantified, and
the percentage of nuclear signals are presented. Data were analyzed by the Student’s t-test and presented as the means ± SD. **P<0.001. LMB, leptomycin-B;
EGF, epidermal growth factor; HECTD1, HECT domain E3 ubiquitin ligase 1. Nuclear signals of (E) HECTD1 and (F) SNAIL were analyzed in wild-type
HeLa cells with not treatment (NT), or with LMB (50 nM) or IVE (1 μM). The percentages of cell nuclear signal are shown. Statistical analysis was performed
using one-way ANOVA with Tukey’s multiple comparisons post hoc test. The data are shown as the means ± SD. **P<0.001. (G) Quantification of SNAIL total
signal intensities of wild-type cells were analyzed in different treatments. The data analyzed by one-way ANOVA and are shown as the means ± SD. n.s., no
significant differences. More than 30 cells in each treatment condition were measured.
which indicated that these cells had a lower cell adhesive ability. The expression level of vimentin remained unaltered, while that of N-cadherin was found to be slightly decreased. Overall, these data suggested that the knockdown of HECTD1 may potentiate EMT.

**Knockdown of HECTD1 sustains EGF signaling.** In cervical cancer cells, EGF has been reported to induce EMT through the upregulation of the expression of SNAIL (28) and via the activation of the AKT and ERK signaling pathways (29). Furthermore, hypoxia activates the EGFR signaling pathway.
Expression of HECTD1 is regulated by miR-210 under hypoxic conditions. Upon screening for factors that regulated the expression levels of Hectd1 in mouse embryonic fibroblasts cells, Hectd1 expression was observed to be downregulated during hypoxic and heat treatment (11). HECTD1 is a putative BH3-only protein under hypoxic conditions (12); it has been reported that hypoxia is involved in the EMT processes (31), and that both miR-21 and miR-210 are also involved in this process (32,33). In this study, miR TarBase was used to identify hypothetical target sequences for HECTD1. Six targeting sequences of miR-21 and miR-210 were found in the 3’UTR of HECTD1. Thus, HECTD1 may be a target of miR-21 and miR-210 (34). By inducing hypoxic conditions in cells using CoCl2, a factor involved in inducing EMT in cancer, the association between the expression levels of HECTD1 and those of miR-21 and miR-210 were investigated. The expression levels of HECTD1 progressively decreased under hypoxic conditions in HeLa cervical cancer cells (Fig. 6A); however, the expression levels of miR-21 and miR-210 were increased in the HeLa cells following CoCl2 treatment (Fig. 6A).

The involvement of miR-21/-210 in the inhibition of HECTD1 expression was further investigated by infecting the cells with their specific antagonirs (α-mir) (35). The presence of the miR-210 antagonist compared with the scramble (α-scr), followed by CoCl2 treatment, resulted in significantly increased mRNA expression levels of HECTD1 (Fig. 6B; P<0.001). Similar results were obtained with miR-21 antagonirs, although to a lesser extent.

HECTD1 expression is positively associated with clinical outcome. To determine whether the genetic abnormalities of HECTD1 expression may affect its function in both cervical cancer cells and in other types of cancer cells, 329 cervical cancer samples from The Catalogue Of Somatic Mutations In Cancer (COSMIC) (36) and 309 samples from The Cancer Genome Atlas (TGCA) were analyzed using whole-exome sequencing (37). A total of 24 mutations were identified throughout the HECTD1 gene, including one frameshift, twenty missense and three silent mutations (Fig. 7A, and Tables SI and SIII). Although all these variants were spread over the entire gene, and they occurred most commonly in those areas which encoded the evolutionally conserved ANK-repeats, the heavily phosphorylated area and the HECT-domain (Fig. 7A). Compared with other types of cancer tissue, such as ovarian cancer, these genetic abnormalities were exclusively observed in small cell carcinoma, squamous cell carcinoma and endocervical adenocarcinoma (Fig. 7A, and Tables SI and SIII).

Using tissue microarrays, the association between the expression of HECTD1 and SNAIL in cervical cancer samples was investigated. A significant inverse association was observed between the nuclear expression of HECTD1 and SNAIL; all 4 samples displayed a low HECTD1 expression in the presence of a high SNAIL expression (Figs. 7B and S5).

Moreover, Kaplan-Meier analysis of squamous cell carcinoma using the HPA (38) revealed that markedly higher HECTD1 expression levels were associated with a longer relapse-free survival (P=4.86x10⁻²; Fig. 7C). By contrast, higher SNAIL expression levels were associated with a shorter relapse-free survival (P=2.25x10⁻²). The association between HECTD1 expression in cancer tissue samples and the survival rate in a number of large public clinical databases was also investigated (39). In breast, gastric, lung and kidney cancer, lower expression levels of HECTD1 were significantly associated with shorter survival times for patients with cancer (Fig. S6). Furthermore, consistent with the role of miR-210 in regulating HECTD1 expression (Fig. 6), higher expression levels of miR-210 were associated with lower expression levels of HECTD1 and a shorter patient survival (Fig. S7), which is similar to results obtained in cervical cancer, where it was reported that the upregulation of miR-210 was associated with a poorer prognosis (40).
Discussion

Previously, Zohn et al (41) and our previous research (11) reported that Hectd1-homozygous mutant embryos display numerous defects during their development and HECTD1 has been observed to interact with proteins involved in several distinct signaling pathways, indicating that HECTD1 may target numerous cellular processes. The present study demonstrated that HECTD1 interacted with SNAIL and promoted its HECTD1-mediated ubiquitination, suggesting that HECTD1 may be one of the numerous E3 ubiquitin ligases regulating the protein stability of SNAIL. Thus, the effects of HECTD1 on SNAIL protein stability and degradation suggested that HECTD1 may be functionally important during tumorigenesis under certain conditions of cellular stress.

The nuclear import and export of HECTD1 and SNAIL are tightly regulated; HECTD1 contains several putative NLS and NES and it has been reported that HECTD1 was pulled-down and co-immunoprecipitated with Importin α3/7 (42), suggesting that HECTD1 is imported into the nucleus via classical nuclear protein transport mechanisms. In the present study, LMB treatment was observed to inhibit the nuclear export of HECTD1, indicating that the nuclear export protein, XPO1/CRM1, is involved in regulating the nuclear retention of HECTD1. It was also demonstrated that HECTD1 interacted with SNAIL and that the cellular localization of SNAIL was paradoxical to HECTD1 following EGF stimulation. Notably, it was observed that the overexpression of SNAIL inhibited HECTD1 expression. SNAIL is a transcriptional factor that exerts global effects on gene expression; it can repress gene expression by using a SNAG domain, a CtBP binding motif or by directly recruiting repressor complexes, thus it is possible that HECTD1 is a SNAIL target gene. The accumulation of SNAIL proteins in the nucleus following HECTD1-KD suggested that the degradation of SNAIL via ubiquitination may occur in the nucleus or that SNAIL translocates to the cytoplasm, where its degradation is subsequently mediated by HECTD1. The nuclear retention of HECTD1 following LMB treatment did not reduce the expression levels of SNAIL; however, the fact that the IVE-induced accumulation of HECTD1 in the cytoplasm induced the degradation of SNAIL favors the later possibility. In agreement with these observations, a recent study (43) used cellular fractionation and western blot analysis to demonstrate that SNAIL was localized in both the cytosol and the nucleus, and the nuclear localization of SNAIL was reduced following the serum starvation of the cells. Of note, it was also observed that the overexpression of SNAIL inhibited HECTD1 expression. It is possible that HECTD1 is a transcriptional target of SNAIL. Thus, future experiments with targeted mutagenesis to all 4 NESs in the ANK repeat region may clarify the mechanisms through which HECTD1 ubiquitinates SNAIL. Previously, several E3-ubiquitin ligases have been reported to play crucial roles in the regulation of SNAIL transcriptional target of SNAIL. Thus, future experiments with targeted mutagenesis to all 4 NESs in the ANK repeat region may clarify the mechanisms through which HECTD1 ubiquitinates SNAIL. Previously, several E3-ubiquitin ligases have been reported to play crucial roles in the regulation of SNAIL translocation. It was observed that the overexpression of SNAIL inhibited HECTD1 expression. SNAIL is a transcriptional factor that exerts global effects on gene expression; it can repress gene expression by using a SNAG domain, a CtBP binding motif or by directly recruiting repressor complexes, thus it is possible that HECTD1 is a SNAIL target gene. The accumulation of SNAIL proteins in the nucleus following HECTD1-KD suggested that
by the EGFR-mediated signaling pathway may be modulated by HECTD1 downstream of EGF signaling. It has previously been reported that HECTD1 is phosphorylated by EGF (44,45); thus, future studies are warranted to investigate whether the phosphorylation of HECTD1 interferes with its nuclear localization.

Under hypoxic conditions, in which CoCl₂ was used to induce cellular responses mediated by hypoxia (46), HECTD1 expression levels decreased, which is consistent with the reduced protein expression levels observed under hypoxia (47). Furthermore, the nuclear translocation of the SNAIL protein increased when cells were exposed to hypoxia (48). These data suggest that the knockdown of HECTD1 expression by hypoxia, or even non-hypoxic conditions that induce HIF-1α stabilization or deregulation of miRNAs, may therefore increase the protein expression levels of SNAIL and downregulate those of E-cadherin, thereby promoting EMT.

The involvement of HECTD1 in EMT in HeLa cells was surprising, since HECTD1-KD cells exhibited no differences in their growth rate compared with the Ctrl. These observations suggested that the selection of HECTD1-KD cells may result in a more aggressive metastasis-like phenotype of malignant cells. Consistent with this hypothesis, the decreased expression levels of HECTD1 were observed to be significantly associated...
with a poor patient survival, not only in cervical cancer, but also in breast and gastric cancer. However, the present study used a small number of patient samples; therefore, further investigations using larger cohorts may provide further insight into the role of HECTD1 in cancer.

Notably, a recent study by Duhamel et al (49) observed that the HECTD1-mediated regulation of ACF7, a +TIPs protein required for cell migration, modulated EMT during metastasis in breast cancer; the decreased expression of HECTD1 promoted ACF7-induced EMT, invasion and metastasis. Thus, the results of the present study, alongside the results from the study by Duhamel et al (49), suggested that HECTD1 may promote EMT through multiple different mechanisms by targeting distinct molecules.

In conclusion, HECTD1 may be one of the E3 ubiquitin ligases that controls the stability of SNAIL proteins, and it may mediate EMT in cervical cancer by regulating cell migration and the expression of transcription factors, such as SNAIL.

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Availability of data and materials

All data generated or analyzed during the present study are included in this article and its supplementary files.

Authors' contributions

HZ, CDG, XW and ZJ conceived and designed the experiment presented in this manuscript. YP performed the CHX chase assay. XW, HZ and CDG wrote the manuscript. All authors discussed the results, and read and approved the final manuscript.

Ethics approval and consent to participate

Not applicable.

Patient consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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