Claudin-3 and Claudin-4 Expression in Ovarian Epithelial Cells Enhances Invasion and Is Associated with Increased Matrix Metalloproteinase-2 Activity

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Abstract

Claudin proteins form a large family of integral membrane proteins crucial for tight junction formation and function. Our previous studies have revealed that claudin-3 and claudin-4 proteins are highly overexpressed in ovarian cancer. To clarify the roles of claudins in ovarian tumorigenesis, we have generated human ovarian surface epithelial (HOSE) cells constitutively expressing wild-type claudin-3 and claudin-4. Expression of these claudins in HOSE cells increased cell invasion and motility as measured by Boyden chamber assays and wound-healing experiments. Conversely, small interfering RNA (siRNA)–mediated knockdown of claudin-3 and claudin-4 expression in ovarian cancer cell lines reduced invasion. Claudin expression also increased cell survival in HOSE cells but did not significantly affect cell proliferation. Moreover, the claudin-expressing ovarian epithelial cells were found to have increased matrix metalloproteinase-2 (MMP-2) activity indicating that claudin-mediated increased invasion might be mediated through the activation of MMP proteins. However, siRNA inactivation of claudins in ovarian cancer cell lines did not have a significant effect on the high endogenous MMP-2 activity present in these cells, showing that malignant cells have alternative or additional pathways to fully activate MMP-2. Taken together, our results suggest that claudin overexpression may promote ovarian tumorigenesis and metastasis through increased invasion and survival of tumor cells. (Cancer Res 2005; 65(16): 7378-85)

Introduction

Tight junctions, the apical-most component of the intercellular junctional complex, form the primary barrier to paracellular transport of solutes across the cells. Tight junctions also play a critical role in establishing and maintaining epithelial cell polarity by acting as diffusion barrier to movement of proteins and lipids within the plasma membrane (1–3). Claudins are the major integral membrane proteins forming the backbone of tight junctions (1, 4, 5). The claudin family consists of 23 transmembrane proteins exhibiting distinct tissue- and development-specific distribution patterns (4, 6). These proteins can form homodimers or heterodimers to produce paired strands between adjacent cells, thereby determining the characteristic permeability properties of different epithelial tissues (7). Disruption of tight junction barrier function and changes in permeability properties have been shown to be associated with a number of pathologic conditions such as kidney disorders, inflammatory bowel disease, pulmonary edema, diarrhea, and jaundice (8–12). In addition, mutations in claudin genes are also linked to genetic disorders. For example, mutation in CLDN14 leads to non-syndromic recessive deafness (13) and the mutated CLDN6 gene has been associated with hereditary hypomagnesemia (14).

Modulations in tight junction structure and function has also been shown in epithelial tumorigenesis (15, 16). A SAGE study by our group previously showed that CLDN3 and CLDN4 are among the most highly up-regulated genes in ovarian cancer (17). Other studies have also identified claudin-3 or claudin-4 as highly up-regulated in ovarian cancer (18–21). A detailed immunohistochemical analysis of claudin-3 and claudin-4 protein expression using an ovarian tissue array recently revealed high levels of expression of these two proteins in the majority of primary ovarian tumors (22). In addition, several other studies have reported aberrant claudin expression in various cancers. Some examples include increased expression of claudin-3 and claudin-4 in prostate and uterine cancers (23, 24), high claudin-4 expression in pancreatic cancer (25, 26), down-regulation of claudin-7 in head and neck cancer (27) and metastatic breast cancer (28), and increase in claudin-3 and claudin-4 in breast cancer (29). However, the exact role of claudin overexpression and the functional importance of these proteins in development of ovarian cancer remain unclear.

The COOH-terminal region of claudin proteins contains a PDZ domain-binding motif that can potentially interact with a number of PDZ domain-containing proteins such as ZO proteins (ZO-1, ZO-2, and ZO-3; refs. 30, 31). These interactions can also serve as adapters for other proteins involved in cell signaling. A number of other cytosolic and nuclear proteins which includes regulatory proteins Rab3b, Rab13, tumor suppressors like PTEN, transcription factors like ZONAB, and HuASH1 have also been shown to interact directly or indirectly with tight junction complex (32–36). These interactions suggest that tight junctions, in addition to acting as barriers to paracellular flow of solutes, may play an important role in regulating other cell functions, such as proliferation and tumor suppression.

In the present study, we overexpressed claudin-3 and claudin-4 in immortalized normal human ovarian surface epithelial (HOSE; which lack endogenous claudin-3 and claudin-4 expression) and studied their effects on tight junction function, cell proliferation, and cell invasion. We also used small interfering RNA (siRNA) technology to knockdown claudin-3 and claudin-4 in ovarian cancer cell lines. We show for the first time that overexpression of claudin-3 and claudin-4 proteins in ovarian cells is associated with phenotypic changes, increasing survival and enhancing invasion and motility of ovarian epithelial cells. Conversely, claudin-3 and claudin-4 reduction in ovarian cancer cell lines leads to the opposite effect with respect to cell invasion. We also show that...
overexpression of claudin-3 and claudin-4 in ovarian cells also leads to activation of matrix metalloproteinase-2 (MMP-2) thus suggesting a mechanism for the increased invasive potential of claudin-expressing ovarian cells. However, siRNA inhibition of claudin in fully malignant cells did not decrease the high endogenous MMP activity present in those cells. Overall, our results suggest that claudin expression is involved in invasion and metastasis of ovarian tumors.

Materials and Methods

Cell lines. HOSE-B, a normal human ovarian surface epithelial cell line immortalized with E6 and E7 (37) was cultured in RPMI medium supplemented with 10% fetal bovine serum (FBS), antibiotics (100 units/ml penicillin and 100 μg/ml streptomycin), and 300 μg/ml G418 and 5 ng/ml epidermal growth factor. IOSE 80, also immortalized normal ovarian surface epithelial cells were obtained from Dr. N. Auerberg (University of British Columbia, Vancouver, Canada; ref. 38). These cells were maintained in Medium 199 (Invitrogen, Carlsbad, CA) supplemented with 10% FBS and antibiotics. The ovarian cancer cell lines HEY, OVCAR-5, and OV167 were maintained in McCoy's 5A medium supplemented with 10% FBS and antibiotics.

Expression constructs. Full-length cDNAs for claudin-3 and claudin-4 were PCR amplified from ovarian cancer cell line OVCR-5 following RNA isolation and reverse transcription. For amplification of CLDN3, the primers used were AGAGAATTCAACATGTTTCCATCTGGGCTACC and GAGGTGCACTTACAGCATGCTCTTGGCTGT. The primers used for CLDN4 amplification were AGAGAATTCAACATGTTTCCATCTGGGCTACC and GAGGTGCACTTACAGCATGCTCTTGGCTGT. The PCR fragment was cloned into a mammalian expression vector pCIneo (Promega, Madison, WI) and the sequence of all the constructs was verified by sequencing.

Generation of cell lines stably expressing claudin-3 and claudin-4. Cells were cultured to 80% confluency and transfections were done using Fugene following the manufacturer's instructions (Roche, Indianapolis, IN). HEY, IOSE-80, and HOSE-B cells were transfected with pCIneo-CLDN4, pCIneo-CLDN3, and pCIneo-EV (empty vector) plasmids. For HOSE-B transfections, each of the vector was cotransfected with pCMV-zeo vector (Invitrogen) and transfected cells were selected with Zeocin (350 μg/ml; Invitrogen). IOSE-80 and HEY clones were selected and maintained in medium supplemented with G418 (500 μg/ml). Colonies were screened by immunoblotting analysis to identify stable clones expressing claudin-3 and claudin-4. To rule out that the effects observed were due to clonal variations, stable cell pools of HOSE and IOSE-80 cells were also established.

Small interfering RNA knockdown experiments. Claudin-3 and claudin-4 specific siRNA oligos were purchased from Ambion, Inc. (Austin, TX). OVCAR-5 and OV167 ovarian cancer cell lines were selected to study effects of claudin knockdown on invasion of ovarian cancer cells. OVCAR-5 is both claudin-3 and claudin-4 positive (22), whereas OV167 is positive for claudin-3. Cells cultured in 6-well plates were transfected with siRNA duplexes using LipofectAMINE 2000 (Invitrogen) following manufacturer's instructions. Mock transfections and nonspecific siRNA duplexes were used as the negative controls. Cells were treated for 48 to 72 hours to allow maximum knockdown, after which they were either harvested for Western blot analysis or used for invasion assays. In addition, culture media collected from the siRNA-transfected cells were analyzed for MMP activity as described below.

Immunoblotting. Confluent cell cultures were washed with HBSS (Invitrogen) and whole cell lysates were made using lysis buffer: 62.5 mmol/L Tris-HCl (pH 6.8), 10% glycerol, and 2% SDS. Protein concentration was determined using the bicinchoninic acid (BCA) assay kit (Pierce, Rockford, IL). Twenty micrograms of total proteins were separated by 10% to 20% SDS-PAGE on Tris-Glycine gels (Invitrogen) and transferred to polyvinylidene difluoride membranes (Millipore Corp., Bedford, MA). The membranes were blocked with 5% nonfat dry milk, washed in TBST buffer, and probed with the primary antibody at the following dilutions: anti-claudin-3, 1:200; anti-claudin-4, 1:250 (Zymed, San Francisco, CA). The blots were then washed and incubated in horseradish peroxidase-conjugated secondary antibody (anti-mouse or anti-rabbit IgG; 1:10,000; Amersham Pharmacia Biotech, Piscataway, NJ). For detection, enhanced chemiluminescence was carried out using the enhanced chemiluminescence kit (Amersham Pharmacia Biotech).

Transepithelial electric resistance measurements. Cells were plated at a density of 1 × 10⁵ per well in 12-well Transwell filters with a membrane pore size of 0.4 μm (Corning Costar, Cambridge, MA). Transepithelial electric resistance (TER) was measured using a Millicell-ERS epithelial volt ohmometer (World Precision Instruments, New Haven, CT). Readings were taken daily for 7 days. The TER values were calculated by subtracting the blank values from the sample values and normalized to the growth area of the monolayer. High-resistance Madin-Darby canine kidney cells were plated as positive controls.

Cell proliferation and clonogenic assays. Single-cell suspensions of claudin-expressing and control HOSE-B cells in complete medium were seeded at equal densities in 6-well plates. Cell count was assessed using a 5-(3-(carboxymethoxyphenyl)-2-(4,5-dimethylthiazolyl)-3-(4-sulfophenyl) tetrazolium, inner salt (MTS) assay by Cell Titer 96 Aqueous One Solution Cell Proliferation Assay kit according to manufacturer's instructions (Promega). The resulting formazan product was quantitated by a multiwell spectrophotometer by measuring absorbance at 490 nm. These experiments were done in triplicates and repeated at least twice.

For clonogenic assays, HOSE-B cells were plated at equal densities in 6-well plates. After 24 hours, cells were transfected with pCIneo-CLDN4, pCIneo-CLDN3, or pCIneo-EV vector (cotransfected with pCMV-zeo vector) using Fugene following the manufacturer's recommendations (Roche). Two independently purified plasmids of each construct were used for transfections. Transfected cells were selected with Zeocin (350 μg/ml) until distinct colonies had formed (10-14 days). The dishes were then rinsed with HBSS before the colonies were stained with 0.25% Crystal violet/20% ethanol for 5 minutes and counted manually.

Invasion and cell migration assay. The cell invasion capabilities of the claudin-expressing clones and the siRNA-transfected cells were determined using a modified Boyden chamber invasion assay (39). Fluoroblock inserts (BD Biosciences, San Jose, CA) of 5-μm pore size were coated with 150 μL of 80 mg/ml of Matrigel (BD Biosciences). Cells were cultured to about 80% confluence and serum starved overnight. On the day of the assay, cells were treated with 5 μmol/L Calcein-AM (AMolecular Probes, Eugene, OR) for 1 hour at 37°C. After the treatment, cells were trypsinized and viable cell count taken. About 50,000 cells were plated on top of each of the coated filters in serum-free medium. An equal volume of the same medium containing 20% FCS was placed in the lower chamber (i.e., the well beneath the filter) to act as a chemoattractant. The assay plate was incubated at 37°C and the total number of invasive cells were measured by taking readings every hour for about 6 hours with an initial 0 hour reading using a Cytofluor4000 set for bottom-read fluorescence. Experiments were repeated at least four times, with triplicates in each experiment. For assessing cell migration, the assay was carried out essentially as above, except that the cells were plated on top of uncoated fluoroblock inserts.

Wound-healing experiment. Cells were grown to confluency on 60-mm cell culture dishes coated with fibronectin, collagen (BD Biosciences), or uncoated plastic dishes. A scratch was made through the cell monolayer using a pipette tip. After washing with HBSS, fresh culture medium was added. Photographs of the wounded area were taken immediately after making the scratch (0 hour time point) and after 24 hours to monitor the invasion of cells into the wounded area.

Analysis of matrix metalloproteinase activity by gelatin zymography. Activities of MMP in the culture medium of cells were assessed using gelatin zymography. HOSE-B clones or siRNA-transfected cells were plated

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1 Unpublished data.
at equal density in T-25 flasks and allowed to grow to 80% confluency. Cells were serum starved for 24 hours after which the cell conditioned medium was collected and concentrated using centrifcon-10 concentrator (Millipore). The protein concentrations in the concentrated medium were determined using the BCA protein assay kit (Pierce). Equal amount of proteins were then separated under nonreducing conditions on a 10% zymogram gel containing 0.1% gelatin (Invitrogen). After electrophoresis, gels were incubated in 2.5% Triton X-100 for 60 minutes to remove the SDS followed by an overnight incubation at 37°C in the zymogram developing buffer (Invitrogen). Gels were then stained for 3 hours in 30% methanol, 10% glacial acetic acid, and 0.5% Coomassie blue G-250 (Bio-Rad Laboratories, Hercules, CA) and destained for 1 hour in 30% methanol/10% glacial acetic acid. Clear bands appear on the Coomassie stained blue background in the areas of gelatinolytic activity. Experiments were carried out with at least two independent lots of culture medium and repeated twice with each lot.

Results

Claudin expression in HOSE cells. To study the possible roles of claudin protein overexpression in ovarian cells, human ovarian cell line HOSE-B was transfected with mammalian expression vector pCI-neo encoding wild-type claudin-3 (pCIneo-CLDN3) or claudin-4 (pCIneo-CLDN4) cDNAs. Cells were also transfected with the empty vector as control. Immunoblot analysis of the selected stable clones using claudin-3- and claudin-4-specific antibodies showed that clone HOSE-CLDN3 expressed high levels of claudin-3 and clones HOSE-CLDN4-1 and CLDN4-2 both expressed claudin-4. The control cells (HOSE-EV) transfected with the empty vector did not express these proteins (Fig. 1).

Claudin expression is known to be important for tight junction formation. To determine whether overexpression of claudin-3 and claudin-4 in ovarian cells results in generation of functional tight junctions, the different clones of HOSE-B cells were grown to confluence and TER was measured. None of the claudin-expressing clones developed TER above background levels (data not shown), indicating that in this ovarian epithelial cell line, expression of claudin proteins does not result in tight junction formation.

Morphologic changes associated with overexpression of claudin-3 and claudin-4. Interestingly, overexpression of both claudin-3 and claudin-4 was associated with morphology changes in HOSE-B cells. Indeed, whereas the control cells exhibited compact growth with cobblestone appearance, the claudin-4-expressing cells were more fibroblastic in appearance, with irregular morphology and elongated processes (Fig. 2). Claudin-3-expressing cells were also found to exhibit irregular patterns of growth compared with the control cells (Fig. 2).

Claudins expression does not affect cell proliferation but increases cell survival in clonogenic assays. To determine whether claudin overexpression can influence the proliferation rate of HOSE cells, MTS assays were carried out on the different clones. HOSE-B cells expressing claudin-3 or claudin-4 did not differ significantly in their proliferation rates compared with that of the empty vector control cells (Fig. 3A-C). Manual counting of growing cells was also done and confirmed the MTS findings (data not shown).

We next investigated the possibility that claudin expression might confer a survival advantage when expressed in epithelial ovarian cells. Clonogenic assays clearly showed that claudin-expressing HOSE-B cells yielded increased colony formation compared with the parental cells (Fig. 3B-C). However, the size of the colonies was not significantly different between claudin-expressing and -nonexpressing cells, an observation consistent with our above results showing that claudin do not affect cell proliferation.

Claudin-3 and claudin-4 expression enhances invasiveness and cell migration of ovarian cells. Differences in invasion between claudin-expressing cells and control HOSE cells were evaluated using a modified Boyden chamber invasion assay. Calcein-labeled cells were placed on matrigel-coated fluoroblok inserts and the cells invading through matrigel were analyzed every hour for up to 6 hours using a fluorimeter. The results show that both claudin-3- and claudin-4-expressing HOSE-B cells were significantly more invasive than the empty vector controls (Fig. 4A). In addition, the rate of cell migration between these cells was also compared using the two-chamber assay with uncoated inserts (instead of matrigel-coated filters). Interestingly, HOSE-B cells expressing claudin-3 as well as claudin-4 showed increased migration compared with the empty vector control (Fig. 4B). In addition, to extend these findings to an additional nontransformed ovarian surface epithelium cell line, IOSE80 cells were transfected with claudin expression vectors and tested for invasion. Similar to the results described above, IOSE80 expressing claudins exhibited increased invasion compared with IOSE80 cells that did not express these proteins (data not shown).

To determine whether these observations could be extended to cancer cells, the ovarian cancer cell line HEY, which does not express claudin-3 or claudin-4, was used. HEY transfectants stably expressing claudin-3 were obtained and tested for invasion. Similar to what we observed with HOSE cells, claudin expression led to an increase in invasion (Fig. 4C). This result shows that the claudin-mediated cell invasion increase also occurs in cancer cells, which may explain why the vast majority of advanced ovarian cancers express these proteins (22).

We also compared the cell motility between the different HOSE clones using a wound-healing/scratch assay, a widely used qualitative method of studying cell migration. The extent of wound closure can be taken as a direct measure of cell motility. Twenty-four hours after generating the wound in the monolayer of cells grown on collagen, the closure was almost complete in claudin-3- and claudin-4-expressing HOSE-B cells, whereas a distinct gap still
Discussion

Changes in permeability properties and loss of cell polarity are hallmarks of epithelial cell tumorigenesis (15). Tight junctions, the structures critical for maintaining these functions in epithelial cells, have been shown to be modulated in a number of epithelial cancers such as colon cancer (16), liver cancer (41), and thyroid cancer (42). Recent studies by our group and several others have shown changes in tight junction–associated claudin protein expression in various epithelial cancers. For example, overexpression of claudin-3 and claudin-4 in ovarian cancer at both the mRNA and protein levels has been reported in many studies (17–24, 29). Additional recent reports from studies on various cancers have revealed that whereas claudin protein expression is up-regulated in certain cancers like prostate cancer (23) and pancreatic cancer (25, 26), these proteins can also be down-regulated in other cancers such as head and neck cancer (27) and breast cancer (28). These results have led to the suggestion that claudin proteins, either alone or in combination with other proteins, may represent useful biomarkers for detection and diagnosis of certain cancers (18).

Although these various studies show that changes in claudin expression are associated with various cancers, the functional significance of these changes in epithelial tumorigenesis has remained unclear. The focus of the present study was to understand the possible functional consequences of claudin overexpression in ovarian tumorigenesis. We found that overexpression of claudin proteins in HOSE cells does not result in the formation of functional tight junctions. This is consistent with our previous finding that claudin-3 and claudin-4 overexpression in various ovarian cancer cell lines was not associated with the ability of these cells to form tight junctions (22). Importantly, we show that claudin-3 and claudin-4 expression in ovarian cancer cells, have been shown to be modulated in a number of epithelial cancers such as colon cancer (16), liver cancer (41), and thyroid cancer (42). Recent studies by our group and several others have shown changes in tight junction–associated claudin protein expression in various epithelial cancers. For example, overexpression of claudin-3 and claudin-4 in ovarian cancer at both the mRNA and protein levels has been reported in many studies (17–24, 29). Additional recent reports from studies on various cancers have revealed that whereas claudin protein expression is up-regulated in certain cancers like prostate cancer (23) and pancreatic cancer (25, 26), these proteins can also be down-regulated in other cancers such as head and neck cancer (27) and breast cancer (28). These results have led to the suggestion that claudin proteins, either alone or in combination with other proteins, may represent useful biomarkers for detection and diagnosis of certain cancers (18).

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metastatic potential of these cells (43). The reasons for this discrepancy are unclear at the present but may be related to tissue-specific differences in claudin function or even to variations in response in different cell lines. Clearly, members of the claudin family are known to be expressed in a tissue-specific manner and may have different function depending on the exact molecular circuitry of the cells (6).

Our observation of increased invasion induced by claudin overexpression in ovarian cancer suggests that these proteins may have unexpected functions in ovarian cancer. In one scenario, the claudin proteins may act in a dominant-negative fashion, inhibiting cell adhesion and promoting invasion. Alternatively, claudins may have intrinsic activities promoting invasion. Our finding that claudin expression leads to increased MMP-2 activity suggests that the second alternative is more likely. There is a precedent for such a mechanism, as it was recently shown that claudin-1 expression could activate MMP-2 activity in kidney cells (40). Considering that MMP-2 has been shown to be important in
ovarian cancer progression (44), our results suggest the possibility that claudin proteins may be involved in the control of motility and invasion through MMP-2, at least early in ovarian tumor progression. Interestingly, siRNA knockdown of claudins do not lead to a decrease in MMP-2 activity in fully malignant cells (data not shown), suggesting that the fully activated state rely on multiple pathways and that inhibition of claudin is not sufficient to reduce MMP-2 activity in these cells. It is interesting that claudin inhibition still leads to a reduction in invasion (Fig. 6), suggesting that other claudin activities (e.g., motility) are still crucial in fully malignant cells.

Metastasis is a complex phenomenon that requires a number of specific steps such as decreased adhesion, increased motility and invasion, proteolysis, and resistance to apoptosis (45). Whereas claudin expression did not significantly alter the cell adhesion properties of the cell (data not shown), it did increase the migration/motility as shown by both Boyden chamber and wound-healing assays. In addition, examination of claudin-3- and...
claudin-4-expressing cells also showed that these proteins, while not having a direct effect on cell proliferation, seemed to affect survival as measured by clonogenic assays. Our results thus show that claudin expression favor three steps known to be important in metastasis (migration, invasion, and survival), suggesting that claudin expression in ovarian and other cancers may be important for metastasis. This is consistent with our previous findings that claudin overexpression is observed in ovarian carcinomas but not in nonmalignant ovarian cystadenomas (22). From a tumor progression standpoint, our current finding that claudin can promote multiple steps known to be important for metastasis is particularly interesting. It has been suggested that the concept of metastasis genes was problematic, as alterations of these genes would not be expected to confer a growth advantage in the primary tumor (46). The discovery that certain genes, such as those encoding claudins, can simultaneously affect processes relevant to both the primary tumor (survival) and to metastasis development (invasion, motility, and survival) may help explain how the metastatic phenotype can be selected for in the primary tumor.

The results presented here suggest for the first time that claudin overexpression may favor cell growth and metastasis in ovarian cancer. Whereas the mechanisms for this phenomenon are still under investigation, it is clear that inhibition of claudin expression or function may represent an interesting strategy for cancer therapy (47), especially in light of our siRNA experiment results. Indeed, preliminary studies with the Clostridium perfringens enterotoxin (CPE), a toxin that specifically binds claudin-3 and claudin-4 have been promising. Experiments have shown that CPE has cytotoxic effects towards breast cancer cells (29), prostate cancer cells (23), and pancreatic cancer cells (25, 48), as long as these cells express claudin-3 or claudin-4. These observations are consistent with the findings in this report suggesting a role for claudin in cell survival. In addition, our present work suggests that therapeutic inhibition of claudins may also reduce cell motility and invasion of claudin-expressing cells, making these protein excellent new targets for cancer therapy.

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