Claudin Proteins in Human Cancer: Promising New Targets for Diagnosis and Therapy

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Abstract

The tight junction proteins claudins are abnormally regulated in several human cancers. In particular, claudin-3 and claudin-4 are frequently overexpressed in several neoplasias, including ovarian, breast, pancreatic, and prostate cancers. Although the exact roles of these proteins in tumorigenesis are still being uncovered, it is clear that they represent promising targets for cancer detection, diagnosis, and therapy. (Cancer Res 2005; 65(21): 9603-6)

Claudins Are Tight Junction Proteins

Tight junctions, together with adherens junctions and desmosomes, form the apical junctional complex in epithelial and endothelial cellular sheets. Adherens junctions and desmosomes are responsible for the mechanical adhesion between adjacent cells, whereas tight junctions are essential for the tight sealing of the cellular sheets, thus controlling paracellular ion flux and therefore maintaining tissue homeostasis (1). Tight junctions also play a crucial role in the maintenance of cell polarity by forming a fence that prevents lateral diffusion of membrane proteins and lipids, thereby maintaining the differential composition of the apical and basolateral domains. Finally, because of the ability of tight junction proteins to recruit signaling proteins (2), tight junctions have also been hypothesized to be involved in the regulation of proliferation, differentiation, and other cellular functions.

When observed by electron microscopy, tight junctions form multiple strands that seem to provide the structural basis for adhesion between adjacent cells (1). Tight junctions are composed of three major integral membrane proteins, occludin, claudins, and junctional adhesion molecules. Although the exact roles of these proteins are not completely clear, it seems that the claudins form the backbone of the tight junction strands. The claudin family of proteins is comprised of 23 members of closely related transmembrane proteins, including claudin-3 and claudin-4, and junctional adhesion molecules. The expression of occludin and claudins, the two major transmembrane proteins that contribute to formation of tight junctions, has been found to be altered in several cancers. An early study in the field showed that claudin was often down-regulated in gastrointestinal tumors (8). Similarly, other studies have shown that claudins are down-regulated in various cancers. For example, claudin-1 has been found to be reduced in breast cancer (9, 10) as well as in colon cancer (11). Claudin-7 has also been found down-regulated in invasive breast cancer (12) and in head and neck cancer (13). These reports of decreased tight junction protein expression in cancer are consistent with the generally accepted idea that tumorigenesis is accompanied by a disruption of tight junctions, a process that may play an important role in the loss of cohesion, invasiveness, and lack of differentiation observed in cancer cells. In addition to the down-regulation of protein levels, phosphorylation of tight junction proteins, including claudins, may affect tight junction function in cancer (14). For example, phosphorylation of claudin-1 by mitogen activated protein kinases (15) and protein kinase C (16), as well as phosphorylation of claudin-5 by cyclic AMP-dependent protein kinase (17, 18) have been reported. Also, WNK4 kinase has been shown to phosphorylate claudin-3 and claudin-4, and decrease tight junction function (19). Interestingly, phosphorylation of claudin-3 and claudin-4 in ovarian cancer cells has been shown to disrupt tight junctions (20).

Claudin Expression in Cancer

The expression of claudin-1 and claudin-4, the two major transmembrane proteins that contribute to formation of tight junctions, has been found to be altered in several cancers. An early study in the field showed that claudin was often down-regulated in gastrointestinal tumors (8). Similarly, other studies have shown that claudins are down-regulated in various cancers. For example, claudin-1 has been found to be reduced in breast cancer (9, 10) as well as in colon cancer (11). Claudin-7 has also been found down-regulated in invasive breast cancer (12) and in head and neck cancer (13). These reports of decreased tight junction protein expression in cancer are consistent with the generally accepted idea that tumorigenesis is accompanied by a disruption of tight junctions, a process that may play an important role in the loss of cohesion, invasiveness, and lack of differentiation observed in cancer cells. In addition to the down-regulation of protein levels, phosphorylation of tight junction proteins, including claudins, may affect tight junction function in cancer (14). For example, phosphorylation of claudin-1 by mitogen activated protein kinases (15) and protein kinase C (16), as well as phosphorylation of claudin-5 by cyclic AMP-dependent protein kinase (17, 18) have been reported. Also, WNK4 kinase has been shown to phosphorylate claudin-3 and claudin-4, and decrease tight junction function (19). Interestingly, phosphorylation of claudin-3 and claudin-4 in ovarian cancer cells has been shown to disrupt tight junctions (20).

Paradoxically, other studies have shown that certain claudin proteins are up-regulated in cancer. In fact, the overwhelming majority of the studies published thus far report an over-expression of claudins in various cancers (see Table 1). One of the first studies reporting this fact was a serial analysis of gene expression (SAGE) study of ovarian cancer showing that CLDN3 and CLDN4 (encoding claudin-3 and claudin-4, respectively) were among the most highly up-regulated genes in this cancer (21). Several additional reports have since confirmed the high
expression of these two claudins in ovarian cancer (22–25). In addition, claudin-3 and claudin-4 have also been reported to be expressed in other cancers, such as breast (26), prostate (27), and pancreatic (28–32) cancers. Other claudins are differentially expressed in a number of human neoplasms and these data are summarized in Table 1.

Roles of Claudin in Cancer

As mentioned above, the loss of claudins and other tight junction proteins in cancer has been interpreted as a mechanism for the loss of cell adhesion and an important step in the progression of cancer to metastasis. Consistent with this hypothesis, a recent study showed that expression of claudin-4 in pancreatic cancer cells reduces invasiveness of these cells (33). In addition, claudin-1 reexpression in cancer cells can lead to increased apoptosis in three-dimensional cultures (34). On the other hand, as discussed previously, many claudins, such as claudin-3 and claudin-4, are typically up-regulated in many cancers (Table 1), suggesting that these proteins may have a positive effect on tumorigenesis. Recent work has shown that, at least in the case of ovarian cells, expression of claudin-3 and claudin-4 may lead to an increase in invasion, motility, and cell survival (35), all characteristics important for metastasis. Consistent with these in vitro findings is a report that claudin-4 expression in pancreatic intraductal papillary mucinous neoplasms was associated with a more invasive phenotype (31). Similarly, expression of claudin-3 and claudin-4 was observed in advanced ovarian cancer but not in ovarian cystadenomas (22). Therefore, the functions of claudins may be highly tissue specific and may depend on the exact molecular circuitry of the cell.

Claudins as Diagnosis Markers and Therapeutic Targets

Because of the high specificity of claudin expression patterns in cancer, it has been suggested that claudins may represent useful molecular markers for many different cancers. For example, a set of four markers, including claudin-3, was found to be sufficient to accurately identify all 158 ovarian cancers tested, including eight early-stage serous cancers (24). In addition, claudin expression may be used as a prognostic indicator because low claudin-1 expression has been shown to be associated with a poor prognosis in stage II colon cancer (11). Claudin-10 expression has also been shown to be an independent prognostic factor for hepatocellular carcinoma recurrence after curative hepatectomy (36).

Interestingly, claudin-3 and claudin-4 are receptors for the Clostridium perfringens enterotoxin (CPE; ref. 37). CPE is a single
agents and, therefore, provide selective drug delivery. Addition-
ally, it has been suggested that, because C-CPE can destroy tight
junctions (41), this peptide may be useful in combination
therapy with conventional chemotherapeutic by increasing drug
delivery to the interior of tumors. However, it seems that
claudin-3 and claudin-4 expression is not necessarily associated
with the formation of functional tight junctions in tumors and
this approach may not be generally viable (22). Because claudins
are transmembrane proteins and typically have two relatively
large extracellular loops (see Fig. 1; ref. 42), these proteins may
also offer promising targets for antibody-based therapy. Anti-
bodies that specifically recognize different extracellular loops
have been produced and shown to specifically bind claudins on
the surface of the cell, providing a proof of principle for the
approach (42).

The advent of gene expression profiling techniques has allowed
the unbiased identification of genes that are differentially
expressed in cancer. Although tight junction proteins have been
studied for their role in tumorigenesis for many years, SAGE
studies of breast (43) and ovarian (21) cancers allowed for the
first time the identification of specific claudin family members as
potential biomarkers for these cancers. Subsequent array analyses
have confirmed these findings and also identified claudins as
proteins frequently altered in cancer (see Table 1). These findings
are important because the unusual expression patterns of clau-
dins suggest utility for detection, diagnosis, and treatment of
drug-resistant cancers. Although clinical trials will be required to
establish this potential, basic research on claudins is likely to
remain valuable for providing important insights into normal and
neoplastic cellular physiology.

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Table 1. Claudin expression in cancer

<table>
<thead>
<tr>
<th>Cancer</th>
<th>Claudin gene</th>
<th>Expression</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breast</td>
<td>CLDN1</td>
<td>Down</td>
<td>(9)</td>
</tr>
<tr>
<td></td>
<td>CLDN7</td>
<td>Down</td>
<td>(12)</td>
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<tr>
<td></td>
<td>CLDN1, CLDN3, CLDN4</td>
<td>Variable</td>
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<tr>
<td></td>
<td>CLDN3</td>
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<td>(26)</td>
</tr>
<tr>
<td></td>
<td>CLDN4</td>
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<td>(26)</td>
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<tr>
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<td>(44)</td>
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<tr>
<td>Colon</td>
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</tr>
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<td>Hepatocellular carcinoma</td>
<td>CLDN10</td>
<td>Up</td>
<td>(36)</td>
</tr>
<tr>
<td>Hepatocellular carcinoma (mouse model)</td>
<td>Cldn7</td>
<td>Up</td>
<td>(46)</td>
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<td>Head and neck squamous cell carcinoma</td>
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<td>Down</td>
<td>(13)</td>
</tr>
<tr>
<td>Squamous cell carcinoma</td>
<td>CLDN1</td>
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<td>(47)</td>
</tr>
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<td></td>
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<td>(21, 24, 25, 48)</td>
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<tr>
<td></td>
<td>CLDN4</td>
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<td></td>
<td>CLDN16</td>
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<td>(49)</td>
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<td>Pancreatic</td>
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<td>Pancreatic (intraductal papillary mucinous neoplasms)</td>
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<td>(31)</td>
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<td>Prostate</td>
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<tr>
<td>Thyroid papillary cancer</td>
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References

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