Heparan Sulfate Enhances Invasion by Human Colon Carcinoma Cell Lines through Expression of CD44 Variant Exon 3

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ABSTRACT

CD44 variant exon (CD44v) 3 is a heparan sulfate-binding isoform of CD44. The role of CD44v3 in invasion and metastasis associated with heparan sulfate in colon cancer cell lines and cases of colon cancer was examined. Expression of CD44v3 mRNA and protein was observed in five of six human colorectal cancer cell lines. Colo320 and WiDr cells expressed CD44v3 at high levels. Heparan sulfate treatment increased the invasive activity of Colo320 and WiDr cells to rates 14.3 and 12.6 times higher, respectively, than that of untreated cells. However, heparan sulfate treatment did not affect cell growth. Repression of CD44v3 protein production by antisense S-oligodeoxynucleotide treatment reduced the binding affinities and capacities for heparan sulfate by Colo320 and WiDr cells in comparison with that of control cells, and it also reduced the invasiveness of both cell lines to one-fifth that of control cells. In heparan sulfate-treated Colo320 cells, the levels of CD44v3 protein in the Triton X-100-insoluble fraction and moesin-precipitated fraction were increased, suggesting that heparan sulfate treatment facilitates association of CD44 molecules with the cytoskeleton. Immunohistochemical analysis showed CD44v3 to be expressed in 21 of 37 (57%) colorectal cancer cases. Positive CD44v3 expression was associated with more advanced pathological stage and poorer prognosis than negative CD44v3 expression. These data support a role for CD44v3 in invasion and metastasis by colorectal carcinoma cells.

INTRODUCTION

CD44 comprises a family of heterogenous integral membrane proteoglycans derived from a single gene (1). The CD44 gene is composed of 20 exons, 10 of which are variably expressed due to alternative splicing (2). CD44 functions primarily in the immune system in processes such as lymphocyte homing (3), lymphohemopoiesis (4), and T-cell activation (5). Recent research in the field has focused on the specificity of CD44 expression in human malignancies. In many types of human malignancy, CD44 acts as a metastasis-related molecule with multiple functions, such as cell-cell and cell-extracellular matrix adhesions, cell migration, and presentation of growth factors and cytokines (6–8). CD44 also plays roles in disease progression and metastasis of colorectal cancer (9). In particular, CD44v6 and CD44v5 are markers of disease prognosis and early transformation of colon cancer, respectively (9, 10).

Polymorphism of the CD44 molecule depends on the numerous patterns of alternative splicing of the extracellular variant domains, glycosylation sites, and glycosaminoglycan attachment sites (11). The hyaluronan-binding sites are located on exons 2 and 5, and the chondroitin sulfate attachment sites are located on exons 5, 15, 16, and 17. The heparan sulfate attachment site is located in exon 8 (CD44v3; Ref. 11). Heparan sulfate is responsible for the presentation of several growth factors, such as heparin-binding epidermal growth factor, basic fibroblast growth factor, VEGF, hepatocyte growth factor, KGF, and some cytokines (12–16). Thus, CD44v3 is thought to contribute to malignant behavior through heparan sulfate.

In the present study, we found expression of CD44v3 in human colon cancer cells to be associated with increased cell invasion after heparan sulfate treatment. Moreover, patients with CD44v3-positive colon cancer have a poorer prognosis than those with CD44v3-negative colon cancer. Human colon cancer cells that express CD44v3 are stimulated by free heparan sulfate to invade, which is also correlated with poor prognosis.

MATERIALS AND METHODS

Cell Culture. Six colorectal carcinoma cell lines were studied. Colo320, DLD1, WiDr, Colo201, and LoVo were obtained from the Japanese Cancer Research Resources Bank. TCO was established in our laboratory (17). All cell lines were routinely maintained in RPMI 1640 (Nissui Pharmaceutical Co. Ltd., Tokyo, Japan) containing 10% fetal bovine serum (Whittaker M.A. Bioproducts Inc., Walkersville, MD) under conditions of 5% CO2 in air at 37°C.

RT-PCR. CD44v3 mRNA transcription was assessed with RT-PCR using 0.5 μg of total RNA extracted by using the RNeasy kit (Qiagen, Hilden, Germany). A primer set for CD44v3 amplification is upper 5’-GTACGTCTTTCAAAT-
ACCA-3′ and lower 5′-GTGGTTGAAATGGTG-3′ (with reference to GenBank accession number AJ251595). PCR products were electrophoresed in a 2% agarose gel and stained with ethidium bromide. The experiment was repeated twice.

**Cell Growth.** Cultured colorectal carcinoma cells were harvested from 80% confluent monolayer cultures by a brief trypsinization with 0.1% trypsin and 0.1% EDTA. The cells were seeded at a density of 2000 cells/well in 96-well tissue culture plates and cultured for 12 h in regular medium. The cells were washed twice with PBS and treated under the conditions mentioned in “Results.” Cell growth was monitored after 24 and 48 h by 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide assay.

**In Vitro Invasion Assay.** A modified Boyden chamber assay was performed to examine the *in vitro* invasion of heparan sulfate-treated Colo320 and WiDr colon cancer cell lines. Polycarbonate filters (pore size, 3 μm; diameter, 5 mm) were glued in the wells of 24-well tissue culture plates. The lower part and/or upper part of the chamber were filled with heparan sulfate (1 or 10 μg/ml). Colo320 and WiDr cells were suspended in 500 μl of regular medium and placed in the upper part of the chamber. After a 12- or 24-h incubation at 37°C, the filters were carefully removed from the inserts, stained with hematoxylin for 10 min, and mounted on microscopio slides. The number of stained cells was counted in whole inserts at ×100 magnification. Invasion activity was quantified by the average count of cells/well.

**Antisense Phosphorothioate Oligodeoxynucleotide Assay.** The 15-mer phosphorothioate oligodeoxynucleotide antisense sequence of the first 15 nucleotides of CD44v3 was synthesized and purified by reverse-phase high-performance liquid chromatography (Espec Oligo Service, Tsukuba, Japan). The sequence was 5′-ATTGCTAGGCATAC-3′ (with reference to GenBank accession number AJ251595), and the random 15-mer for negative control was a random mixture of oligonucleotides with all four nucleotides at every position. Cells were pretreated with 4 μM antisense or random S-oligodeoxynucleotide for 6 days, with medium exchange and addition of antisense or random S-oligodeoxynucleotide every 2 days before being used for experiments. When CD44v3 antisense or random S-oligodeoxynucleotide (2, 4, and 8 μM) was added to the culture medium of Colo320 and WiDr cells, inhibition of growth due to cytotoxicity from the antisense or random S-oligodeoxynucleotide was not observed after 6 days of culture with each treatment.

**Cell Lysate.** Cells were seeded on 3.5-cm cell culture plates and cultured in RPMI 1640 with 10% fetal bovine serum. The cultured cells were washed three times with PBS. Cells were lysed in boiling SDS-lysis buffer [50 mM Tris-HCl (pH 7.5), 5 mM EDTA, 1 mM EGTA, 1 mM Na3VO4, 2% SDS, 10 μg/ml leupeptin, and 50 μg/ml PMSF] for 10 min. The extract was centrifuged, and the supernatant was used for immunoblotting.

For extraction of ionizing detergent-soluble and -insoluble fractions, cultured cells were washed with PBS containing 1 mM CaCl2, 1 mM Na3VO4, 10 μg/ml leupeptin and 50 μg/ml PMSF. Cells were lysed in lysis buffer A [50 mM Tris-HCl (pH 7.5), 5 mM EDTA, 1 mM EGTA, 1 mM Na3VO4, 1% Triton X-100, 10 μg/ml leupeptin, and 50 μg/ml PMSF] for 30 min on ice. The crude extract was centrifuged, and supernatant constituted the Triton-soluble fraction. Pellets were extracted with SDS-lysis buffer, boiled for 10 min, and centrifuged. Supernatant constituted the Triton-insoluble fraction.

**Immunoblotting.** Fifty μg of lysate were subjected to immunoblot analysis after 12.5% SDS-PAGE followed by electrophoretic transfer onto nitrocellulose filters. The filters were first incubated with a primary antibody, anti-CD44v3 (Chemicon International, Inc., Temecula, CA), and then incubated with peroxidase-conjugated antibody (Medical & Biological Laboratories Co. Ltd., Nagoya, Japan) in the secondary reaction. The immune complex was visualized using the enhanced chemiluminescence Western blot detection system (Amersham, Aylesbury, United Kingdom).

**Immunoprecipitation.** For immunoprecipitation, the lysates were precleaned in lysis buffer with protein A agarose (Santa Cruz Biotechnology, Santa Cruz, CA) for 1 h at 4°C and subsequently centrifuged. The supernatants were incubated with anti-moesin antibody (Santa Cruz Biotechnology) and protein A agarose for 16 h at 4°C. Precipitates were collected by centrifugation and washed five times with lysis buffer for SDS-PAGE. For loading control, 5 μl of each preimmunoprecipitated sample (lysat diluted with buffer) were slot-blotted onto nitrocellulose membrane and stained with Coomassie Blue.

**[3H]Heparan Sulfate Binding Assay.** Heparan sulfate oligosaccharide (Seikagaku Corp., Tokyo, Japan; mean molecular weight, 10,000) was nonenzymatically labeled with [3H]acetic anhydride (Amersham) in sodium acetate to a specific activity range of 30,000–31,000 mCi/μmol (18). Cells were seeded in 6-well culture plates at 1 × 105 cells/well. After 24 h, the cells were washed with the binding medium (RPMI 1640 containing 1% BSA) and treated with various dilutions of [3H]heparan sulfate ranging from 10 ng to 100 μg/ml (with non-specific binding) or without (specific binding) unlabeled [3H]heparan sulfate (200 μg) in 0.5 ml of binding medium. Binding was carried out for 4 h at 4°C. After incubation, the medium was removed, and the dishes were washed four times with PBS. Cells were dissolved in 0.1 N NaOH containing 0.05% SDS, and dishes were rinsed with more water. The radioactivity was measured with a liquid scintillation counter. Data were obtained from duplicate experiments.

**Surgical Specimens.** Thirty-seven formalin-fixed, paraffin-embedded archival surgical specimens from Hiroshima University Hospital of human primary colon adenocarcinomas that had invaded the subserosal layer were chosen at random. The 37 cases contained 8 nodal metastasis-positive cases (Dukes’ C) and 10 liver metastasis cases (Dukes’ D), which were confirmed by histopathological examination. The remaining 19 cases showed no lymph node metastasis (Dukes’ B). It was confirmed from operational findings and clinical examinations that all Dukes’ B and C patients did not have any distant metastases at the primary operation. All cases were also followed-up at the hospital. Prognosis study was based on the clinical database of the patients.

**Immunohistochemistry.** Consecutive 4-μm sections were immunostained using the immunoperoxidase technique described previously (19). Antigenicity was retrieved with microwave treatment (1000 W, 10 min) in citrate buffer. Anti-
CD44v3 antibody (Chemicon International, Inc.) was used at 1:200 for 2 h at room temperature, followed by treatment with peroxidase-conjugated antigoat IgG antibody (Medical & Biological Laboratories Co. Ltd.) at room temperature. The specimens were color-developed by diaminobenzidine solution (DAKO Corp., Carpinteria, CA) and counterstained with Meyer’s hematoxylin (Sigma Chemical Co., St. Louis, MO).

RESULTS

mRNA Transcription and Protein Expression of CD44v3 and Effect of Heparan Sulfate Oligosaccharides on Growth of Colon Cancer Cells. Five of six cell lines expressed both mRNA and protein of CD44v3 at varying levels, but Colo201 cells did not express CD44v3 mRNA and protein (Fig. 1A). Colo320 and WiDr cells, which expressed high levels of CD44v3 mRNA and protein, were used for additional studies. Cell growth was almost similar between heparan sulfate-treated cells and untreated Colo320 cells (Fig. 1B). Different concentrations of heparan sulfate did not affect the growth characteristics of cells.

Effect of Heparan Sulfate Oligosaccharides on Invasiveness of Colon Cancer Cells. After a 24-h treatment with 10 μg/ml heparan sulfate applied in the lower chamber, Colo320 and WiDr cells invaded type IV collagen-coated membrane at rates 14.3 and 12.6 times greater, respectively, than that of untreated cells (Table 1). Both cell lines treated with 10 μg/ml heparan sulfate applied in the upper chamber also invaded at rates 8.1 and 8.5 times greater, respectively, than that of untreated cells.

Effect of CD44v3 Antisense S-oligosaccharide on CD44v3 Protein Expression, Heparan Sulfate-binding Activity, and Invasiveness of Colon Cancer Cells. To confirm the invasion-promoting effect of heparan sulfate mediated by CD44v3, Colo320 and WiDr cells were treated with 4 μM CD44v3 antisense or random S-oligosaccharide to reduce CD44v3 expression. After treatment, cells were used in three types of experiments: (a) immunoblot analysis (Fig. 2A); (b) [3H]heparan sulfate oligosaccharide binding assay (Fig. 2B); and (c) in vitro invasion assay after heparan sulfate treatment (Fig. 2C). In antisense S-oligosacchodie-nucleotide-treated Colo320 and WiDr cells, the levels of CD44v3 protein production decreased by one-third and one-fifth, respectively, of the level of production in random S-oligosaccharide-nucleotide-treated cells (Fig. 2A). The binding capacities and affinities for [3H]heparan sulfate were compared between antisense- and random S-oligosaccharide-nucleotide-treated cells (Fig. 2B). In antisense S-oligosaccharide-nucleotide-treated Colo320 cells, the binding affinity (dissociation constant, Kd) and binding capacity (maximal binding, Bmax) for heparan sulfate were reduced to 18% and 27%, respectively, of those of random S-oligosaccharide-nucleotide-treated cells. In antisense S-oligosaccharide-nucleotide-treated WiDr cells, the binding affinity and capacity for heparan sulfate were also reduced to 11% and 71%, respectively, of those in random S-oligosaccharide-nucleotide-treated cells. Reduction of heparan sulfate binding capacity by antisense S-oligosaccharide-nucleotide treatment diminished the invasive potential of Colo320 and WiDr cells to one-fifth of pretreatment levels (Fig. 2C).

Effect of Heparan Sulfate on Association between CD44v3 Protein and the Cytoskeleton. The intracellular signals that are activated after heparan sulfate oligosaccharide treatment were examined (Fig. 3). Triton X-100-insoluble CD44 is associated with ERM proteins, which are linked to the cytoskeleton (20). Total protein levels of CD44v3 were not altered after heparan sulfate treatment. CD44v3 protein levels were reduced in the soluble fraction and increased in the insoluble fraction of heparan sulfate-treated Colo320 cells. To confirm the
physical association between CD44v3 and ERM proteins, immunoprecipitation was performed. Anti-moesin immunoprecipitates were reacted with anti-CD44v3 antibody, and the amount of CD44v3 coimmunoprecipitated with moesin increased after heparan sulfate oligosaccharide treatment. No obvious alterations in phosphotyrosine levels were detected after heparan sulfate treatment (data not shown).

Immunohistochemical Detection of CD44v3 Protein in Surgical Specimens of Colorectal Cancer. We examined CD44v3 production in human colorectal cancer specimens by immunohistochemistry. Immunoreactivity was observed at the cytoplasmic membrane and on the cytoplasm of cancer cells, but not in normal mucosal cells (Fig. 4, a and b). Twenty-one of 37 (57%) colorectal cancer cases showed CD44v3 immunoreactivity without deviated distribution to the invasive front. CD44v3-positive cases showed a higher frequency of metastasis (Dukes’ C and D) than did CD44v3-negative cases (Dukes’ B; \( P = 0.0006 \) by \( \chi^2 \) test; Table 2). Cancer cells showed strong staining for CD44v3 at the metastatic foci in the lymph nodes and liver. Study of survival revealed that CD44v3-positive cancer patients showed significantly reduced survival as compared with CD44v3-negative patients (\( P = 0.0081 \) by a Cox proportional hazards model; Fig. 5). A multivariate statistical examination revealed that CD44v3 expression was the second significant factor, after the final pathological stage (Dukes’ classification), for predicting overall survival of the patients (Table 3).

**DISCUSSION**

We have demonstrated that heparan sulfate enhances the invasive capacity of colon cancer cells by a mechanism mediated by CD44v3 protein. Recent studies have focused on the mechanism of heparan sulfate enhancement of cancer invasion and metastasis (21, 22). Heparan sulfate and a heparan sulfate-modified isoform of CD44, CD44v3, have been implicated in growth factor presentation at sites of inflammation and the cancer host microenvironment. Many heparan sulfate-binding growth factors have been reported, including the insulin-like growth factor family, the fibroblast growth factor family, transforming growth factor \( \beta \), hepatocyte growth factor (15, 23), KGF (16), interleukin 8 (24), and VEGF (13). Binding to heparan sulfate facilitates the interactions of these growth factors with specific receptors (23). The fact that CD44v3 binds to and presents basic fibroblast growth factor and heparin-binding
epidermal growth factor (12) suggests that CD44v3 is also
responsible for heparan sulfate-associated growth factor presen-
tation.

In the present experiments, heparan sulfate oligosaccharide
treatment increased cell invasion activity in vitro on type IV
collagen. Invasion was inhibited by repression of CD44v3 pro-
duction by antisense S-oligodeoxynucleotide treatment. One
explanation for this result is that Colo320 and WiDr cells
express several growth factors, such as KGF (25) and VEGF
(26), that bind to heparan sulfate in association with CD44v3
molecules, and these growth factors might be displaced by high
concentrations of heparan sulfate oligosaccharide. It is also
possible that binding of heparan sulfate to CD44v3 generates
intracellular signals. Two types of intracellular signals generated
by CD44 have been reported. One is tyrosine phosphorylation of
non-receptor-type tyrosine kinases of src family members in-
cluding c-yes, c-fgr, fyn, lyn, and lck (27–29). However, we
could not detect phosphotyrosine signals after heparan sulfate
treatment (data not shown). The other intracellular signal gen-
erated by CD44 is association of CD44 through ERM proteins
with actin filaments of the cytoskeleton. This is closely associ-
ated with rho activation and hence with acceleration of cell
motility (20, 30, 31). In heparan sulfate-treated Colo320 cells,
CD44v3 protein was translocated from the Triton X-100-soluble
fraction to the Triton X-100-insoluble fraction through the in-
teraction of CD44v3 with moesin. These findings suggest that
heparan sulfate treatment induces an association between CD44
protein and the cytoskeleton and that this may enhance the
invasion capacity of cells.

In several types of human cancers, CD44v3 expression is
associated with the clinical course of the disease. CD44v3
expression is closely correlated with nodal metastasis in breast
cancer (32) and with positive surgical margins, a high Gleason
score, and the presence of perineural infiltration in prostate
cancer (33). Patients with CD44v3-positive vulvar cancer had
poorer prognoses for both relapse-free and overall survival (34).
However, CD44v3 expression was not predictive for tumor
spread or patient survival in cases of gastric cancer (35). Our
present results indicate that colon cancers positive for CD44v3
expression show greater disease progression and a poorer prog-

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**Table 2** Number of cases positive for CD44v3 expression in
colorectal carcinomas by immunohistochemical analysis

<table>
<thead>
<tr>
<th>No. of cases</th>
<th>CD44v3 positive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>37</td>
</tr>
<tr>
<td>Dukes’ stage*</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>19</td>
</tr>
<tr>
<td>C</td>
<td>8</td>
</tr>
<tr>
<td>D</td>
<td>10</td>
</tr>
</tbody>
</table>

* Dukes’ B, invasion to or beyond proper muscle layer with no
  metastasis; Dukes’ C, any invasive depth with lymph node metastasis; Dukes’ D, distant metastasis.

* Difference of stage distribution between CD44v3-positive cases was examined by $\chi^2$ test ($P = 0.0006$).

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**Table 3** Prediction of survival periods of colorectal carcinomas by a
multivariate statistical analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$P^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD44v3 expression (positive, negative)</td>
<td>0.0235</td>
</tr>
<tr>
<td>Dukes’ classification (stage B, stage C–D)</td>
<td>0.0011</td>
</tr>
<tr>
<td>Histological type (well, moderate-poor)</td>
<td>0.3541</td>
</tr>
<tr>
<td>Tumor size (&lt;4 cm, ≥4 cm)</td>
<td>0.8734</td>
</tr>
</tbody>
</table>

* $P$ was calculated by Cox proportional hazards model.
nosis than do CD44v3-negative cancers. Whereas cancer cells producing CD44v3 were a minority within the tumor, CD44v3 expression was frequently found in lymph node metastases, suggesting that cancer cells that express CD44v3 possess a metastatic advantage.

REFERENCES


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