CD44v8-10 Is a Cancer-Specific Marker for Gastric Cancer Stem Cells

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Abstract
The surface marker CD44 has been identified as one of several markers associated with cancer stem cells (CSC) in solid tumors, but its ubiquitous expression in many cell types, including hematopoietic cells, has hindered its use in targeting CSCs. In this study, 28 paired primary tumor and adjacent nontumor gastric tissue samples were analyzed for cell surface protein expression. Cells that expressed pan-CD44 were found to occur at significantly higher frequency in gastric tumor tissues. We identified CD44v8-10 as the predominant CD44 variant expressed in gastric cancer cells and verified its role as a gastric CSC marker by limiting dilution and serial transplantation assays. Parallel experiments using CD133 failed to enrich for gastric CSCs. Analyses of another 26 primary samples showed significant CD44v8-10 upregulation in gastric tumor sites. Exogenous expression of CD44v8-10 but not CD44 standard (CD44s) increased the frequency of tumor initiation in immunocompromised mice. Reciprocal silencing of total CD44 resulted in reduced tumor-initiating potential of gastric cancer cells that could be rescued by CD44v8-10 but not CD44s expression. Our findings provide important functional evidence that CD44v8-10 marks human gastric CSCs and contributes to tumor initiation, possibly through enhancing oxidative stress defense. In addition, we showed that CD44v8-10 expression is low in normal tissues. Because CD44 also marks CSCs of numerous human cancers, many of which may also overexpress CD44v8-10, CD44v8-10 may provide an avenue to target CSCs in other human cancers. Cancer Res 74(9); 1–12. ©2014 AACR.

Introduction
Gastric cancer is a major cause of cancer-related death worldwide, with low survival and high recurrence rates for patients with advanced disease (1–3). Therefore, new therapies for treatment of gastric cancer are urgently needed. The cancer stem cell (CSC) hypothesis proposes that a specific subset of CSCs is primarily responsible for initiating and maintaining tumor growth (4, 5), a proposition that may explain the high frequency of relapse and resistance to current therapeutic modalities that focus on reduction of tumor bulk without considering tumor heterogeneity. Definitive CSC markers for gastric cancer have yet to be characterized, although several studies have identified gastric CSCs from cell lines (6–9).

CD44 is a cell surface transmembrane glycoprotein encoded by the CD44 gene, a 20-exon DNA segment (10), of which exons 1–5 and 16–20 are spliced together and translated into CD44s, the standard isoform. In addition, the variant exons 6–15 can be alternatively spliced and assembled in different combinations with the standard exons to generate other variant (CD44v) protein isoforms. More recently, CD44 has been recognized as a CSC marker in several types of cancer (11). As CD44s is ubiquitously expressed in many cell types (12–16), its usefulness as a CSC marker may be limited. Furthermore, conflicting data in the field implicate CD44 in both tumor suppression and progression (17–19), largely attributed to the expression of alternatively spliced variants. In light of this, we investigated the role of CD44 splice variants in gastric cancer. In this study, we isolated gastric CSCs using two well-known markers for CSCs, EpCAM and CD44. Further investigation of the expression of CD44 variants in gastric cancer revealed that CD44v8-10 is specifically upregulated in tumor cells, and its expression confers an advantage in tumor initiation.

Materials and Methods

Study approval
All patient tissue samples were collected with informed patient consent from National University Hospital Singapore (Singapore) according to the Institutional Review Board guidelines. All animal experiments were conducted with the approval of Institutional Animal Care and Use Committee in the National University of Singapore.
Isolation and purification of single cells from dissociated tumor tissue

Samples were washed twice in sterile Hank's Balanced Salt Solution (HBSS) before mincing finely with scalpels. Tissue pieces were incubated in 0.1% dithiothreitol/PBS to remove mucus and washed twice in HBSS before incubation at 37°C for 2 hours in 0.2-μm sterile filtered DMEM/F12 media (Invitrogen) containing 100 U/mL hyaluronidase (H1136; Sigma), 300 U/mL collagenase type II (C6885; Sigma), 5 ng/mL human recombinant insulin (12585; Invitrogen), and 1 ng/mL hydrocortisone (H2270; Sigma). Digestion mixture was washed twice in HBSS by centrifugation at 1,200 × g for 8 minutes. Pelleted material was resuspended in HBSS and filtered using a 40-μm cell strainer (Falcon) to collect single cells. Single-cell suspensions were passed through LD and dead cell removal columns (Miltenyi Biotec) to remove cellular debris and dead cells. All procedures were carried out under sterile conditions.

Flow cytometric analysis and cell sorting

Single cells were counted with a hemocytometer using Trypan blue exclusion of dead cells. A total of 1 × 10^6 and 3 × 10^6 cells were used for direct and indirect staining, respectively. For cells isolated from clinical gastric samples, CD45^± blood cells and GlyA^+ erythroid precursors were gated out and excluded from analysis (Supplementary Fig. S1). For xenograft-derived cells, murine H-2Kd MHC class I alloantigen-positive (H-2Kd^+) cells were excluded from analysis. Cells were analyzed on a BD LSRII flow cytometer (BD Biosciences). Median fluorescence intensity (MFI) values were calculated using FlowJo software (TreeStar). Cell sorting was performed on a BD FACSAria (BD Biosciences). Sytox Blue (S34857) from Invitrogen was used to exclude dead cells in all analyses. Post-sort analysis was performed to ensure that purity of cell fractions was ≥90%. Cells were washed twice in sterile PBS and counted before resuspension in Matrigel (BD Biosciences) for xenograft transplant assays. Rat anti-human CD44v8-10 specific antibody was kindly provided by Prof. H. Saya (Keio University, Tokyo, Japan) and was generated as previously described (20). Briefly, CD44v8-10 was overexpressed in McA RH-7777 rat epithelial cells that do not express any endogenous isoforms of CD44. These cells were then used to immunize rat host to raise CD44v8-10 antibodies. Other antibodies used are described in Supplementary Materials and Methods.

Patient-derived xenograft models

Single-cell suspensions or minced tissue pieces were mixed at 2:1 with sterile HBSS/Matrigel (BD Biosciences) in a final volume of 200 μL per injection and administered subcutaneously. For CD44 overexpression studies, vector control and CD44-transfected cells were injected on opposite flanks of the same animals to minimize experimental variability from differences in recipient mouse hosts. For cell-dosing experiments, 20 to 25,000 sorted or unsorted cells were injected per site. Six- to 8-week-old nonobese diabetic/severe combined immunodeficient (NOD/SCID) or NOD/SCID/HuR2γ^– (NSG) mice were used for xenograft transplantations and anesthetized intraperitoneally with a cocktail of xylazine (11 mg/kg) and ketamine (72 mg/kg). Mice were checked weekly for tumor formation and sacrificed when tumors were 1.5 cm in diameter (usually 6–10 weeks) or after 20 weeks (if no tumor was observed).

Primary gastric samples and cell lines

Primary gastric cancer cells used in our study include GC59, GC71, GC101, GC121, and GC123. Established patient-derived xenograft lines include GC16, GC21, GC38, GC45, GC84, and GC119. Primary cell line GC38-adh was established in vitro from GC38 xenograft line as described below. Other cell lines used were MKN28 (JCRB Cell Bank, Japan), SNU5 (American Type Culture Collection), and TMK1 (provided by Dr. Patrick Tan, Duke-NUS, Singapore). These cell lines were authenticated by 16-loci short tandem repeat (STR) profiling (LGIC Standards) in November 2013.

Primary cell culture

All cultures were maintained in humidified 37°C incubators supplemented with 5% CO2. Primary cell cultures were established from GC38 xenograft tumors. Tumor spheroids were first derived from freshly minced tumor pieces in a 10-cm tissue culture dish in serum-free low-glucose Dulbecco's Modified Eagle Medium (DMEM; Invitrogen; details in Supplementary Data). Spheroids were propagated by dissociation with TrypLE (Invitrogen) for 10 minutes at 37°C, centrifugation at 1,200 × g for 8 minutes, and resuspension in PBS before passing them through a cell strainer (30 μm) to remove dead cell aggregates. Live single cells were then replated in serum-free DMEM at a density of 10,000 single cells per 35-mm dish. GC38 tumor spheroids were EpCAM^+ as characterized by flow cytometric analysis, with 55% to 85% CD44^+ (EpCAM^+ CD44^+) cell populations. Established cultures of tumor spheroids were used to derive adherent monolayer primary cultures of GC38 cells. Spheroids were transferred to DMEM containing 10% FBS, which facilitated the growth of adherent cells after a period of 3 to 4 weeks. These adherent cells were passaged and expanded as the GC38-adh primary cell line.

In vivo limiting dilution assays

Non-mouse cells from each xenograft were sorted on the basis of the indicated surface phenotypes and injected subcutaneously in NSG mice. Each mouse received the same cell dose of indicated fractions from the same xenograft and was either harvested when tumor generated from any fraction reached 1.5 cm diameter (usually 6–10 weeks), or 20 weeks later. Mice were considered negative for tumor formation when there was no palpable tumor. For functional assays of CD44s and CD44v8-10 overexpression, cells were sorted for the respective population and injected into mice at indicated doses. The frequency of cancer-initiating cells was calculated using the Web-based tool Extreme Limiting Dilution Assay (ELDA; Walter and Eliza Hall Institute, Parkville VIC, Australia).

Cell proliferation assays

GC38-adh cells, stably transfected with pcDNA3 vector, CD44s, or CD44v8-10, were fractionated for the relevant population and 3,000 cells were seeded in each of five replicate wells in a 96-well plate. Cell proliferation over a 5-day period was measured using WST-1 cell proliferation reagent (Roche...
Diagnosics) according to the manufacturer’s instructions. Briefly, 10 μL of WST-1 reagent was added per 100 μL of culture medium and incubated for 2 hours before measurement of absorbance at 460 nm in a plate reader (Tecan). Absorbance readings were normalized against blank wells and growth curves were plotted with data points showing mean ± SD.

Depletion of CD44 in TMK1 cells

Short hairpin RNA (shRNA) that targets CD44 and scrambled control shRNA were obtained from Origene (TG314080). CD44 shRNA consisted of two different shRNA sequences targeted against human CD44 (NM_000610). Cells were transfected with shRNA plasmids using Lipofectamine 2000 (Invitrogen) as described above. For CD44 “rescue” experiments, TMK1 cells were cotransfected with 6 μg each of CD44 shRNA plasmids (Origene) and either CD44s, CD44v8-10, or pcDNA3 vector as shRNA-resistant rescue constructs. These shRNA-resistant rescue constructs were engineered by mutating relevant residues in the CD44 plasmid sequences targeted by the shRNA constructs. The mutagenesis primers and shRNA sequences are provided in Supplementary Table M1. Transfections were performed as described above. TMK1 cells were sorted by flow cytometry for the relevant populations before injecting them into NSG mice for tumor formation assay.

ELISA

ELISA was performed using human CD44 ELISA kit (Ab45912; Abcam). Conditioned media (100–300 μL) from cells cultured in 10-cm dishes was assayed according to the manufacturer’s protocol.

Histopathology

Tissue samples were fixed in 10% formalin and embedded in paraffin before sectioning at 4-μm thickness. Hematoxylin and eosin (H&E; Sigma) staining was performed on all sections and evaluated by a pathologist.

Statistical analysis

All error bars represent the mean ± SD. Paired two-tailed Student t tests and Fisher exact test were performed using GraphPad Prism (GraphPad Software). Chi-squared (χ²) tests were performed using the Web-based software for ELDA (http://bioinf.wehi.edu.au/software/elda/; Walter and Eliza Hall Institute of Medical Research; ref. 21). For all statistical tests, P < 0.05 was considered to be significant. For flow cytometric data, MFI was calculated using FlowJo software (TreeStar) where relevant.

Results

Identification of EpCAM and CD44 as surface markers for gastric CSCs

A candidate approach was undertaken to identify putative gastric CSCs from primary gastric cancer specimens because various surface markers have previously been used to describe CSCs from different cancers. Cells from 28 paired primary tumor and adjacent nontumor tissues from patients with gastric cancer (Supplementary Table S1) were isolated and analyzed by flow cytometry for potential CSC markers including CD44, CD133, CD34, CD117, CD90, CD166, and EpCAM as well as CD45 (hematopoietic cells), CD31 (endothelial cells), and CD140b (fibroblasts). Of these, gastric cancer cells were positive for EpCAM, CD44, CD133, and CD166 expression. In particular, EpCAM levels were significantly higher in cells from 28 gastric tumors compared with paired adjacent nontumor tissue (P = 0.0006; Fig. 1A). EpCAM is a well-established epithelial marker that is highly expressed in most carcinomas including gastric cancer (22, 23). Also, EpCAM⁺ but not EpCAM⁻ cells initiated tumors in mice (Supplementary Fig. S1C), suggesting that gastric CSCs should be a subpopulation within the EpCAM-expressing tumor cells; hence, we used EpCAM as an identifier for gastric tumor epithelial cells and to exclude nontumor cells.

Following this, flow cytometric analyses of EpCAM-expressing cells indicated the absence of CD90⁺, CD34⁺, and CD117⁺ cells, and a high proportion of CD166⁺ cells (60%–70%) in both tumor and nontumor sites. CD44⁺ and CD133⁺ cells were found in the range of 0.8% to 54% and 0.6% to 45%, respectively. Analyses of CD44⁺ or CD133⁺ cells in the EpCAM⁺ fraction isolated from 21 paired tumor and nontumor patient samples revealed a consistently higher proportion of CD44⁺ cells (P = 0.0124), but not CD133⁺ cells at the tumor site (P = 0.861; Fig. 1B–D). Nevertheless, CD44 and CD133 were further analyzed as potential markers for gastric CSCs.

We established a robust gastric cancer xenograft model by subcutaneous implantation of primary tumors taken from patients with gastric cancer. Histologic analysis verified that all xenograft tumors recapitulated the original primary tumors, as shown for GC16 (well-differentiated), GC21 (moderately differentiated), and GC38 (poorly differentiated; Fig. 2A). The proportion of EpCAM⁺ CD44⁺ cells in GC16, GC21, and GC38 xenografts was 3.6%, 58%, and 44%, respectively (Fig. 2B). Nevertheless, EpCAM and CD44 were further analyzed as potential markers for gastric CSCs than CD133.

Serial transplantations were also performed by reisolating EpCAM⁺ CD44⁺ cells from first transplants in NSG mice and injecting these cells into recipient mice as second transplants. The proportion of CD44⁺ cells in xenograft tumors of both first and second transplants remained unchanged from the original tumors (Fig. 2D). Similarly, xenograft tumors of both first and second transplants showed the same histology (Fig. 2E). Because the injected cells are ≥95% CD44⁺, this suggests that EpCAM⁺ CD44⁺ cells are able to differentiate to reestablish tumor heterogeneity of the original patient tumor as well as to...
self-renew and sustain tumor growth in serially passaged xenografts. This also demonstrates that CD44\(^{+}\) cells retained tumor-forming potential during serial transplantation. Taken together, these data indicate that gastric CSCs are enriched in the EpCAM\(^{+}\)CD44\(^{+}\) fraction of gastric tumors.

**CD44v8-10 is the predominant CD44 variant in gastric cancer xenografts and marks gastric CSCs**

To determine the expression of CD44 variants in xenograft tumors, PCR primers were designed in constant exons 5 and 16/17, flanking the variable region of the CD44 gene (Fig. 3A). PCR amplification of cDNA from xenograft tumors GC16, GC21, and GC38 generated two main products—324 and 720-bp fragments whose sequences were verified to be CD44s, the standard transcript in many cell types, and CD44v8-10, a variant first identified in colon carcinomas, respectively (Fig. 3A; ref. 24). By quantitative PCR (qPCR) analysis, we found that the level of CD44v8-10 transcript is highest in GC21, followed by GC38 and GC16 (Fig. 3B). Most importantly, levels of CD44v8-10 transcripts correlated with the estimated number of gastric CSCs in the unsorted fractions (Fig. 2C and Table 1).

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**Figure 1.** EpCAM-expressing cells in gastric cancer tissues are tumor epithelial cells containing subpopulations of CD44\(^{+}\) and CD133\(^{+}\) cells. Flow cytometric analyses of surface marker expression in cells isolated from 28 paired gastric tumors and adjacent nontumor tissue. A, EpCAM levels in 28 gastric tumors compared with adjacent nontumor tissue. MFI was calculated using FlowJo software (Supplementary Fig. S1B). Horizontal bars, the mean value. Patient clinical information is included in Supplementary Table S1. B, proportion of CD44\(^{+}\) and CD133\(^{+}\) cells in gastric cancer compared with adjacent nontumor tissue. Representative flow cytometry data plots from 3 patients with gastric cancer (GC16, GC59, and GC71) are shown. Proportion (%) of CD44\(^{+}\) or CD133\(^{+}\) cells within the EpCAM\(^{+}\) population is shown in the top right quadrant. C and D, proportion of CD44 and CD133 cells in EpCAM-expressing cells isolated from 21 paired tumor and nontumor sites. Cells were stained with antibodies against EpCAM and CD44 or CD133 and analyzed by flow cytometry. Data were analyzed for statistical significance using Student paired t test.
We next used antibodies specific to CD44v8-10 to determine whether the EpCAM⁺CD44⁺ cells identified in clinical samples using pan-CD44 antibody consist of CD44v8-10-expressing cells. The specificity of CD44v8-10 antibody was verified as follows: first, the antibody binds to CD44v8-10 but not CD44s when either of these was transiently expressed in MKN28, a gastric cancer cell line devoid of CD44 expression (Supplementary Fig. S2A). Second, the extracellular domain of...
CD44v8-10 (sol-CD44v8-10) but not sol-CD44s blocked the binding of the CD44v8-10 antibody to gastric cancer cells (Supplementary Fig. S2B), indicating that binding of the antibody to these cells is specific to the CD44v8-10 protein.

Using this CD44v8-10–specific antibody, we found that the majority of EpCAM+CD44+ cells identified using pan-CD44 antibodies are CD44v8-10 cells. This is shown in a representative sample GC101, where in the EpCAM+ fraction, 79% of pan-CD44–expressing cells are CD44v8-10–positive (Fig. 3C; isotype controls are shown in Supplementary Fig. S2C). This observation was further substantiated by analysis of two other clinical samples GC121 and GC123 showing that majority of the CD44 population in the tumor consists of CD44v8-10 (Fig. 3D and E). Strikingly, CD44v8-10 is absent in hematopoietic CD45+ cells (Fig. 3C), in contrast to CD44s that is expressed in hematopoietic cells.

To determine that CD44v8-10 marks gastric CSCs, we prospectively isolated the CD44v8-10 cells and subjected them to cancer-initiation assay by limiting dilution analyses. CD44v8-10–specific antibody was used to fractionate CD44v8-10+ cells from gastric tumor xenografts GC45 and GC84 to high purity (Fig. 4A) before performing limiting dilution assays. We injected the unsorted, CD44v8-10–, and CD44v8-10/C0 cell fractions into NSG mice at cell doses of 2,000, 200, and 20. In the GC45 xenograft, the CD44v8-10 fraction showed a 51- (P = 2.5 × 10^{-19}) and 3.8-fold (P = 0.00217) enrichment of CSCs compared with the CD44v8-10/C0 and unsorted fractions, respectively (Fig. 4B). Similarly for GC84, CD44v8-10 fractions were enriched for CSCs by 84- (P = 1.4 × 10^{-18}) and 6-fold (P = 0.00242) compared with CD44v8-10/C0 and unsorted cell fractions, respectively (Table 2 and Fig. 4B). We also serially transplanted CD44v8-10+ cells reisolated from CD44v8-10 first transplant tumors of GC45 and GC84 into second transplant recipients, and observed the same percentage of CD44v8-10+ and CD44v8-10/C0 cells as the first transplant xenograft tumors (Fig. 4C). Histology of serially transplanted xenograft tumors recapitulated that of the initial xenografts (Fig. 4D), confirming that CD44v8-10 indeed marks a population of CSCs, which are able to form tumors as well as regenerate the original tumor heterogeneity. However, as

**Table 1.** Limiting dilution assay for EpCAM+CD44+ cells

<table>
<thead>
<tr>
<th>Gastric cancer cell source</th>
<th>Cell dose</th>
<th>Number of mice with tumors/number of mice injected (%)</th>
<th>Estimated gastric CSC in 10,000 cells</th>
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<tbody>
<tr>
<td><strong>GC16</strong></td>
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<tr>
<td></td>
<td>25,000</td>
<td>5/5 (100%)</td>
<td>1 in 8,140 (4,782–13,855)</td>
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<tr>
<td></td>
<td>10,000</td>
<td>4/5 (80%)</td>
<td>1 in 72 (35–148)</td>
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<tr>
<td></td>
<td>5,000</td>
<td>5/12 (42%)</td>
<td>1 in 14,770 (7,586–28,758)</td>
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<tr>
<td></td>
<td>2,000</td>
<td>2/9 (22%)</td>
<td>1 in 87 (18–173)</td>
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<tr>
<td></td>
<td>1,000</td>
<td>0/5 (0%)</td>
<td></td>
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<tr>
<td></td>
<td>500</td>
<td>0/3 (0%)</td>
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<td></td>
<td>100</td>
<td>0/8 (0%)</td>
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<tr>
<td></td>
<td>20</td>
<td>0/8 (0%)</td>
<td></td>
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<tr>
<td><strong>Estimated stem cell frequency (confidence intervals)</strong></td>
<td>1 in 87 (18–173)</td>
<td>1 in 14,770 (7,586–28,758)</td>
<td>1 in 267 (156–458)</td>
</tr>
<tr>
<td><strong>Estimated gastric CSC in 10,000 cells</strong></td>
<td>1.2</td>
<td>138.9</td>
<td>0.68</td>
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<tr>
<td><strong>GC21</strong></td>
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<tr>
<td></td>
<td>5,000</td>
<td>2/2 (100%)</td>
<td>1 in 83 (48–144)</td>
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<td></td>
<td>4,000</td>
<td>3/3 (100%)</td>
<td>1 in 1,455 (882–2,400)</td>
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<td></td>
<td>2,000</td>
<td>12/12 (100%)</td>
<td>1 in 1,455 (882–2,400)</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>3/5 (60%)</td>
<td>1 in 1,455 (882–2,400)</td>
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<td>400</td>
<td>8/10 (80%)</td>
<td>1 in 1,455 (882–2,400)</td>
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<tr>
<td></td>
<td>100</td>
<td>5/10 (50%)</td>
<td>1 in 1,455 (882–2,400)</td>
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<tr>
<td><strong>Estimated stem cell frequency (confidence intervals)</strong></td>
<td>1 in 1,455 (882–2,400)</td>
<td>1 in 1,455 (882–2,400)</td>
<td>1 in 1,455 (882–2,400)</td>
</tr>
<tr>
<td><strong>Estimated gastric CSC in 10,000 cells</strong></td>
<td>37.5</td>
<td>120.5</td>
<td>6.9</td>
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<td><strong>GC38</strong></td>
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<td></td>
<td>2,000</td>
<td>12/13 (92%)</td>
<td>1 in 140 (76–259)</td>
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<td></td>
<td>500</td>
<td>4/7 (57%)</td>
<td>1 in 1,142 (660–1,977)</td>
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<td>300</td>
<td>5/6 (83%)</td>
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<tr>
<td></td>
<td>50</td>
<td>2/13 (15%)</td>
<td>1 in 1,142 (660–1,977)</td>
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<tr>
<td><strong>Estimated stem cell frequency (confidence intervals)</strong></td>
<td>1 in 1,142 (660–1,977)</td>
<td>1 in 1,142 (660–1,977)</td>
<td>1 in 1,142 (660–1,977)</td>
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<tr>
<td><strong>Estimated gastric CSC in 10,000 cells</strong></td>
<td>20.1</td>
<td>71.4</td>
<td>8.7</td>
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</table>

Abbreviation: ND, not determined.
CD44v8-10 cells may consist of both CD44\(^+\) and CD44\(^-\) populations, we next compared the tumor-initiating potential between CD44\(^+\) and CD44v8-10\(^+\) fractions and observed that when injected at a dose of 200 cells, CD44v8-10\(^+\) cells formed tumors with higher frequency than CD44\(^+\) cells (Fig. 4E). This clearly demonstrates that CD44v8-10\(^+\) cells within the CD44\(^+\) fraction have enhanced tumor-initiating capability compared with CD44\(^+\) cells.

The sphere formation assay is widely used as an in vitro method to evaluate stem cell activity in normal tissue as well as putative CSCs (25); hence, we established tumor spheres from explants of GC38 xenograft tumor and confirmed that the sphere-forming cells are indeed human epithelial cells that express EpCAM (Supplementary Fig. S3C and S3D). However, when we isolated CD44v8-10\(^-\) and CD44v8-10\(^+\) cells from the spheroid culture, we found that both isolated subpopulations formed spheres in serum-free medium (Supplementary Fig. S3E and S3F). Moreover, other gastric xenograft lines did not survive as long-term tumor sphere cultures regardless of CD44v8-10 expression. As it has been noted that not all spheres originate from stem cells (26), our results suggest that sphere-forming in vitro limiting dilution assay may not be a reliable surrogate for the more definitive in vivo limiting dilution assay in the identification of surface markers for gastric CSCs.

**CD44v8-10 is upregulated in gastric tumor samples and plays a functional role in tumor initiation**

CD44 variant–specific primers were designed for quantitative real-time PCR (qRT-PCR) analysis on another cohort of 26 gastric tumors and matched adjacent nontumor tissues. The CD44v6 variant has also been reported to promote tumor growth and metastasis (27, 28); hence, we also investigated its expression level in gastric tumors. Our results show that CD44v8-10 expression was significantly elevated (\(P = 0.0029\)) in tumor compared with adjacent nontumor tissue, whereas CD44s and CD44v6 expression levels were similar in both tumor and adjacent nontumor tissue (Fig. 4F).

To determine whether CD44v8-10 plays a functional role in gastric cancer initiation, we next established and characterized a clonal primary gastric cancer cell line GC38-adh from a
patient with gastric cancer. We used GC38-adh cells for over-expression studies, as the percentage of CD44-expressing cells was relatively low (5%) in this cell line. CD44s and CD44v8-10 was stably overexpressed in GC38-adh cells (Fig. 5A) and their proliferation rate was monitored over a period of 5 days, during which we observed that the in vitro growth rate of these cells was not significantly different (Fig. 5A). We next sorted CD44s- and CD44v8-10–overexpressing cells and injected these fractions into NSG mice at limiting cell doses to determine their ability to initiate tumors. Our data show that CD44v8-10–overexpressing cells were able to initiate tumors with higher efficiency than vector control cells (P = 0.0168; Supplementary Table S3A; Fig. 5B).

In reciprocal experiments, we performed shRNA-mediated knockdown of total CD44 in gastric cancer cells. We used TMK1 cells because >99.9% of the cells express the CD44v8-10 isoform (Fig. 5C). We observed that injection of 200 CD44-depleted cells (Supplementary Fig. S4B) did not form tumors, compared with scrambled control shRNA (Supplementary Fig. S4C). To "rescue" this knockdown phenotype, we expressed shRNA-refractory CD44v8-10 as well as CD44s and CD44v8-10 expression in 26 primary tumor samples versus adjacent nontumor tissue, normalized to 18S rRNA internal control. Horizontal bars, the mean value. Paired Student t test was performed for statistical significance.

Discussion

Recent developments in the stem cell field have further validated the CSC concept. By using genetic techniques to trace the cells during tumor progression in mice, three research...
Takaishi and colleagues (6) have previously identified the use of CD44 as a gastric CSC marker and further characterized these cells. Several other studies have reported the use of EpCAM and CD44 cell surface markers, suggesting that the combination of CD44 and CD54 may not be sufficient to enrich for CSCs in gastric tumors. CD44 marks gastric CSCs, it is also highly expressed in both tumor and nontumor cells. More importantly, although CD44v8-10 surface protein can be recognized and identified using a CD44v9-specific antibody (Supplementary Fig. S2A and S2B; refs. 20, 35), which allowed us to isolate and study CD44v8-10-expressing cells.

We used several patient-derived xenografts models in our identification of gastric CSCs and showed that pan-CD44 or CD44v8-10 expression alone was sufficient to predict enrichment of gastric CSCs. As CD44 is a known Wnt-signaling target (36), we characterized the xenograft models by microarray analyses and found that despite differences in expression of Wnt target genes, such as LGR5, ZNF43, ASCL2, CLDN2, SP5, and AXIN2 (36, 37), there was no correlation between gene expression profiles of the Wnt pathway and CD44v8-10 expression (data not shown), indicating that molecular differences in these xenografts had no bearing on the function of CD44v8-10 in tumor initiation. We also evaluated p53 mutation status in a selected number of xenograft lines because p53 has been reported to inhibit expression of the CD44 cell surface molecule (38). Although we observed p53 mutations in some xenograft lines, we found no correlation between p53 mutation status and proportion of CD44v8-10-expressing cells in the xenograft tumor (Supplementary Table S4).

CD44v8-10 (CD44R1) was first described in colon cancer and was found to be upregulated in primary and metastatic tumors but rarely expressed in normal mucosa of adults (24). In the Gan mouse, a genetic model for gastric tumorigenesis, the mouse homolog of human CD44v8-10 is expressed in preneoplastic regions of the stomach, from which tumor-initiating cells are thought to arise, suggesting that CD44v8-10 may be a marker for gastric tumor-initiating cells in the mouse (39). CD44v8-10 also seems to promote metastasis in colon, pancreatic, and breast cancer cells (24, 40, 41), with significant positive correlation to tumor recurrence and mortality (24). Using antibodies directed against the CD44 variant exon 9, CD44v9 expression in primary tumors was significantly and

### Table 2. Limiting dilution assay for EpCAM+CD44v8-10+ (Ep−CD44v−) cells

<table>
<thead>
<tr>
<th>Gastric cancer cell source</th>
<th>Cell dose</th>
<th>Number of mice with tumors/number of mice injected (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GC45</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,000</td>
<td>Unsorted</td>
<td>Ep−CD44v− 13/13 (100%) Ep−CD44v− 13/13 (100%) Ep+CD44v+ 8/13 (62%)</td>
</tr>
<tr>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimated stem cell frequency (confidence intervals)</td>
<td>1 in 139 (82–237) 1 in 36 (17–78) 1 in 1,844 (988–3,440)</td>
<td></td>
</tr>
<tr>
<td>Estimated gastric CSC in 10,000 cells</td>
<td>72</td>
<td>277.8</td>
</tr>
<tr>
<td><strong>GC84</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20,000</td>
<td>Unsorted</td>
<td>Ep−CD44v− 4/4 (100%) Ep−CD44v− 4/4 (100%) Ep+CD44v+ 3/4 (75%)</td>
</tr>
<tr>
<td>2,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimated stem cell frequency (confidence intervals)</td>
<td>1 in 454 (187–1,108) 1 in 75 (34–166) 1 in 8,859 (3,320–23,641)</td>
<td></td>
</tr>
<tr>
<td>Estimated gastric CSC in 10,000 cells</td>
<td>22</td>
<td>133.3</td>
</tr>
</tbody>
</table>
positively associated with tumor recurrence and mortality (35, 42). These studies indicate the importance of CD44v9 as a prognostic marker but functional studies that define CD44v9-expressing cells as gastric CSCs are lacking. Because the CD44v8-10 isoform includes exon 9, our current findings may provide further functional and mechanistic explanation for these correlative observations.

Overexpression of CD44v8-10 but not CD44s resulted in cells with higher tumor-initiating potential in vivo although we did not observe any significant changes in proliferation upon ectopic expression of either protein in vitro. This suggests that CD44v8-10 may enhance tumor-initiation capability of gastric cancer cells by increasing their resilience to adverse conditions such as hypoxia or oxidative stress. Indeed, there is evidence that CD44v8-10 stabilizes the cystine transporter xCT, thereby promoting the ability of cancer cells to defend themselves against reactive oxygen species (20). In light of these observations, CD44v8-10 cells may also be responsible for conferring resistance to therapeutic treatment; therefore, it is of paramount importance to eradicate this subpopulation of cells for effective treatment of gastric cancer.

In conclusion, we have shown that CD44v8-10 is the major variant found in CD44-expressing gastric cancer cells. The CD44v8-10 cell population is enriched with gastric CSCs, and CD44v8-10 plays a functional role in tumor initiation. More importantly, CD44v8-10 expression is low in normal tissues (both epithelial and hematopoietic cells; Fig. 3C), thus, making it an ideal target for directed therapy against gastric CSCs. In addition, our study has broader implications as CD44 also marks CSCs of numerous cancers (11), many of which may also...
overexpress CD44v8-10. However, as pan-CD44 antibodies were used for prospective isolation of CSCs in most studies, this remains to be investigated. CD44 plays diverse physiologic roles in many different tissues (43), thereby undermining its suitability as a CSC target. For instance, injection of antagonizing anti-CD44 antibody induces systemic shock in mice (44), and other side effects of anti-CD44 treatment have also been documented (45). Unlike CD44s that is expressed in many normal tissues, CD44v8-10 is cancer specific; therefore, our discovery of CD44v8-10 as a gastric CSC marker opens a critical window for therapeutic targeting of CSCs in other human cancers.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Authors’ Contributions

Conception and design: A. Shabbir, J.B.Y. So, S.L. Chan


Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): W.M. Lau, H.S. Chong, K.A.P. Lopez, A.Y.L. Tay, M. Salto-Tellez, A. Shabbir, J.B.Y. So, S.L. Chan

Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): W.M. Lau, J.B.Y. So, S.L. Chan

Writing, review, and/or revision of the manuscript: W.M. Lau, A. Shabbir, J.B.Y. So, S.L. Chan

Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): W.M. Lau, E. Teng, H.S. Chong

Study supervision: J.B.Y. So, S.L. Chan

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References


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