Toward the Prognostic Significance and Therapeutic Potential of HER3 Receptor Tyrosine Kinase in Human Colon Cancer

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Abstract

Purpose: Abnormal accumulation and dysregulation of the epidermal growth factor receptor family member HER3 is associated with the development of various human cancers including those of the breast, lung, and ovary. We have previously shown that in melanoma HER3 is frequently overexpressed and is associated with poor prognosis. However, the importance of HER3 in colon cancer and its putative prognostic significance is still unknown.

Experimental Design: HER3 expression was analyzed in primary colon tumors from 110 patients by immunohistochemistry and correlated with time of progression. Parallel to this, the influence of HER3 overexpression on cell proliferation, migration, invasion, and apoptosis was investigated in four different colon cancer cell lines including DLD-1, LoVo, CaCO2, and T-84.

Results: HER3 was detected at high frequency and exclusively at the membrane of the primary tumors. Elevated HER3 expression levels may serve as a putative prognostic marker because it associates with cell proliferation and decreased time to disease progression. High HER3 protein expression as well as phosphorylation levels were detected in tested cells. HER3 downregulation by RNA interference abrogated cell proliferation, migration, and invasion. In addition, suppression of HER3 resulted in a G2–M cell-cycle arrest, induced apoptosis, and led to morphologic changes in colon cancer cell lines. Furthermore, application of a monoclonal antibody specific to the extracellular portion of the receptor reduced heregulin-β1–induced migration and invasion and also induced apoptosis in colon cancer cell lines.

Conclusion: We postulate that HER3 is critically involved in colon cancer progression and may serve as a novel target for therapeutic intervention.

Introduction

Colon cancer is a common type of bowel cancer that originates from the neoplastic transformation of epithelial cells of the colon through an adenoma precursor stage. It is considered as the fourth most common malignancy in the Western world and the third most frequent cause of cancer-related mortality (1, 2). Underlying molecular mechanisms of colon cancer formation have been studied extensively during the last years. Multiple genetic and epigenetic aberrations were shown to initiate the development of colon cancer and to drive its progression (3–9). Understanding the genetic basis of colon cancer, however, has not yet led to highly effective therapies other than complete surgical removal of the tumor. In this regard, molecular characterization of predictor genes and signaling pathways controlling colon cancer growth is instrumental to new drug design and the refinement of cancer chemotherapy for individual patients.

HER3 (ErbB3) is a member of the human epidermal growth factor receptor (EGFR/HER) tyrosine kinases family. Its gene maps to human chromosome 12q13.2 and results in a protein of about 180 KDa (10–12). HER3 overexpression was illustrated in a wide range of cancers including those of breast, ovary, lung, and prostate, as well as melanoma (13–16). This genetic feature has been correlated with poor prognosis in most of the cases (15–18). Subsequent to its activation, HER3 effectively couples to the PI3K/AKT pathway, thereby controlling different biologic outcomes including cell proliferation, motility, and cell survival (19). HER3 has in fact 6 tyrosine phosphorylation motifs with XX (20–23). HER3 is unique in the ErbB family in that it has been shown to have weak or no
**Translational Relevance**

As a member of the epidermal growth factor receptor tyrosine kinases family, HER3 pseudokinase was shown to play a crucial role in regulation of oncogenic processes. Dysregulation of this receptor is associated with the progression of different human cancers including those of the breast and colon. Our studies show that HER3 overexpression represents a putative prognostic marker because it correlates with reduced patient survival. We also show that HER3 is overexpressed in human colon cancer cell lines and that HER3 is functionally associated with cancer-related cell processes. Our findings identify HER3 as a promising target for colon cancer therapy development.

tyrosine kinase activity (24). Because of this property, HER3 phosphorylation after hererulin activation is dependent on heterodimerization with other ErbB family members (25–27). In human breast cancer, HER3 interacts with HER2 and thereby generates a potent oncogenic dimer that promotes tumor development and progression (27). Indeed, the HER3/HER2 heterodimer represents the most potent mitogenic complex among EGFR family members. It contributes synergistically to cell transformation and to malignant properties of cancer cells (28). Recent work of van der Horst and colleagues showed that hererulin-induced activation of HER3 in glioma-derived cell lines results in the phosphorylation of a cytoplasmic kinase protein, PYK2 (28). Interestingly, a monoclonal antibody targeting HER3 was shown to reduce proliferative as well as migratory properties of breast cancer cell lines (29). Consistent with this, it was shown that increased HER3 expression predicts poor prognosis of patients with melanoma and that treatment of melanoma cell lines by a monoclonal antibody targeting HER3 blocks cell proliferation, migration, and invasion (16). Interestingly, it was shown recently that treatment of HER2-amplified breast cancers with HER2-targeting tyrosine kinase inhibitors (TKI) leads to a rapid compensatory increase in HER3 expression, localization, and signaling activity (30). Thus, HER3 is considered as a crucial receptor, which could be a novel target for the treatment of different human cancers.

In this study, our aim was to determine whether HER3 could be considered as a determinant for poor prognosis in patients with colon cancer and whether it has a relevant role in transmitting proliferative, survival, and motility signals in colon cancer. We therefore analyzed HER3 expression levels in a panel of 110 patients with colon cancer. We conducted clinicopathologic correlations using multivariate analysis. Furthermore, we analyzed the inhibitory effect of HER3 siRNA as well as of HER3 monoclonal antibody treatment on different oncogenic processes including cell proliferation, survival, migration, and invasion. Our findings support a putative prognostic relevance of HER3 in colon cancer and implicate this HER family member as promising novel target for colon cancer treatment.

**Materials and Methods**

**Clinical samples and statistical analyses**

HER3 expression was evaluated using formalin-fixed, paraffin-embedded (FFPE) colon cancer samples of patients who underwent surgical tumor resection at the Ludwig-Maximilians-Universität München, München, Germany, between 1994 and 2005. Follow-up data were recorded by the Munich cancer registry. Paraffin-embedded tissue samples of primary tumors were available in 110 cases. The median age of the patients at the time of diagnosis was 67 years. Clinicopathologic characteristics of the study population are summarized in Supplementary Table S1. For inclusion models, age, gender, tumor grade, and T-category were considered as covariables. Frequency data were analyzed using the \( \chi^2 \) test. Cancer-specific survival was calculated from the date of primary surgery to the date of cancer-associated death. Survival data of patients whose death was not attributable to colorectal cancer or whose follow-up ended before death were censored. Survival analysis was done by the Kaplan–Meier method and the groups were compared with the log-rank test. Univariate and multivariate analyses were based upon the Cox regression model. Cases with missing data were excluded from multivariate analyses. Statistical procedures were done using SPSS version 13.0 (SPSS Inc.). \( P < 0.05 \) was considered as statistically significant.

The study was approved by the ethics committee of the Medical Faculty of the Ludwig-Maximilians-Universität München.

**Immunohistochemistry, scoring of HER3 expression, and statistical analyses**

All tumors were arrayed in quadruplicate on tissue microarrays using 1.0-mm diameter punch sets (Beecher instruments). Five-micrometer sections were prepared for immunohistochemical staining. As the primary antibody, we used anti-HER3 (clone C-17, 1:50; Santa Cruz). Staining was conducted on a Ventana Benchmark autostainer with the XT Ultraview DAB Kit (Ventana Medical Systems). All slides were counterstained with hematoxylin. To exclude unspecific staining, isotype and system controls were included. HER3 expression was scored semiquantitatively, considering membranous immunostaining of the tumor cells only. Depending on the intensity of staining, HER3 expression was classified as weak, intermediate, or strong.

**Cell lines, compounds, and culture conditions**

All cell lines were purchased from American Type Culture Collection, and propagated in a humidified atmosphere containing 7% \( \text{CO}_2 \) at 37°C. The human DLD-1 colon cancer cell line was maintained in RPMI-1640 supplemented with 10% fetal calf serum (FCS). Human LoVo and CaCO2 colon cancer cells were cultured in Ham’s F-12 and Dulbecco’s Modified Eagle’s Media, respectively, both...
supplemented with 20% FCS and 1% l-glutamine. T-84 cells were maintained in Ham’s F-12/DMEM high glucose (1:1) medium supplemented with 5% FCS and 1% pyruvate. All media were supplemented with 1× penicillin/streptomycin (Gibco). 5-Fluorouracil and propidium iodide were purchased from Sigma. Heregulin-β1 was purchased from R&D Systems and diluted in PBS before use.

**RNA interference**

HER3 siRNA duplexes were synthesized by Ambion. Two independent siRNAs were used in all experiments. The targeted sense and antisense sequences were as follows respectively: sense-1, 5’-GGCAGUCGCCUGCGCAUACUtt-3’; antisense-1, 5’-UGGCCAUGCAUGCCAGGUGG-3’; sense-2, 5’-GGCAGUCGGUACUGGCCACUtt-3’; and antisense-2, 5’-AGUCCUCAGACACUCUGGtcg-3’. The GL-2 siRNA from Dharmaco was used as a negative control with the following sequence: 5’-CCUCUCAGCGGAUAUCCUGGAtt-3’ (sense), 5’-UCGAAGUAUUCCGCGUACGtt-3’ (antisense). The siRNA transfection was conducted using Lipofectamine RNAiMax (Invitrogen) according to the manufacturer’s recommendation.

**Western blotting, immunoprecipitation, and immunofluorescence**

Cells were either left nonstimulated or were stimulated with 100 ng/ml heregulin-β1 for 24 hours and lysed on ice in lysis buffer. Antibodies to phospho-HER3 (Tyr1289), p85, phospho-akt (Ser473), cyclin B1, phospho-extracellular signal–regulated kinase (ERK) 1/2, phospho-mTOR (Ser2448), and phospho-Rb (Ser780) were all purchased from Cell Signalling. Horseradish peroxidase (HRP)-conjugated rabbit antibodies were from Sigma. The anti-HER3 (clone 2F12) monoclonal antibody or rabbit polyclonal primary antibody was from Upstate and anti-HER3 (C-17) for immunoprecipitation, a specific HER3 antibody was from Bio-Rad. Anti-tubulin, anti-β-actin, and HRP-conjugated mouse secondary antibodies were from Sigma. The anti-HER3 (clone 2F12) antibody was from Upstate and anti-HER3 (C-17) for immunohistochemistry was from Santa Cruz. Anti-α2β1 was purchased from Abcam. For immunoprecipitation, a specific antibody was from Dharmacon and anti-HER3 (C-17) for immunoprecipitation, a specific antibody was from Dharmacon and anti-HER3 antibody was from Abcam. The anti-HER3 (clone 2F12) monoclonal antibody or rabbit polyclonal primary antibody was from Upstate and anti-HER3 (C-17) for immunoprecipitation, a specific HER3 antibody was from Bio-Rad.

**For immunodetection, HER3- and GL-2–transfected cells were fixed in 4% paraformaldehyde, permeabilized with 0.5% Triton X-100 for 10 minutes, and blocked in 4% bovine serum albumin. The sections were incubated with a primary antibody against vimentin (1:100; Santa Cruz) and then with the appropriate secondary antibody (Molecular Probes and Jackson ImmunoResearch). Nuclear DNA was finally counterstained with 4’,6-diamidino-2-phenylindole (DAPI; 0.02 μg/mL) and micrographs were taken using a Zeiss Axioplan 2 with MetaVue software (Molecular Devices).**

**Proliferation assay**

Cells were transfected with HER3 or GL-2 siRNA using Lipofectamine RNAiMax (Invitrogen). The cells were either grown in their appropriate media or serum starved in medium containing 1% FCS for 24 hours and subsequently stimulated with 100 ng/ml heregulin-β1. The cell number was counted (Coulter Counter; Becton Dickinson) at the indicated time points. The data are shown as mean ± SD.

**Cell-cycle analysis**

To analyze the cell cycle, HER3-knockdown cells as well as control cells were harvested and fixed with 70% ethanol in PBS. Cells were then resuspended in 0.5 mL PBS containing propidium iodide and DNase-free RNase for 2 hours and subsequently subjected to flow cytometric analysis (Becton Dickinson Biosciences) to determine cell-cycle profiles. At least 10,000 cells were analyzed from each sample.

**Migration and invasion assays**

Cells transfected with HER3 or GL-2 siRNA using Lipofectamine RNAiMax (Invitrogen) were serum starved in medium containing 0.1% FCS for 24 hours and seeded either onto a membrane or onto a growth factor–reduced Matrigel-coated membrane with 8-μm pores of a modified Boyden chamber (Schubert and Weiss) containing 500 μL serum-free medium; 10% FCS medium served as a chemotactrant. After 20 or 24 hours of incubation at 37°C, migrating and invading cells, respectively, were stained with crystal violet and washed in PBS. The cells in the insert were removed by wiping gently with a cotton swab. Cells on the reverse side of the insert were examined and photomicrographs were taken (Zeiss Axiosvert 300 Microscope). At least, 10 random fields per filter were counted for quantification. The data are shown as mean ± SD.

**Apoptosis assay**

HER3- or GL-2–transfected cells were treated with either 10 or 20 μmol/L 5-fluorouracil or dimethyl sulfoxide as a negative control. After 72 hours, floating cells were collected and adherent cells were trypsinized. After centrifugation, cells were incubated for 2 hours in a propidium iodide buffer (0.1% sodium citrate, 0.1% Triton X-100, and 20 μmol/L propidium iodide) and subsequently subjected to flow cytometric analysis (Becton Dickinson Biosciences). Apoptotic cells were identified as the sub-G1 to G1 peak and...
quantified using the CellQuest Pro Software (Becton Dickinson).

**HER3-blocking antibody: migration, invasion and apoptosis experiments**

The HER3-blocking antibody (clone 105.5) was purchased from Upstate. To assess the HER3 phosphorylation state, cells were serum starved for 24 hours, incubated with 10 μg/mL blocking antibody for 1 hour, stimulated with 100 ng/mL heregulin-β1 for 2 hours, lysed, and subjected to immunoprecipitation using a specific HER3 antibody (homemade; cl.1B4.C3).

MDA-MB-468 breast cancer cells were already described to be inhibited by the anti-HER3 antibody (clone 105.5; ref. 29) and served as a positive control. The data are shown as a percentage of inhibition relative to control cells.

The cell migration and invasion assays were conducted as described previously (16, 29, 31). Briefly, cells were seeded in 10-cm plates and serum starved in medium containing 0.1% FCS for 24 hours. Cells (400,000/mL) were then incubated with 10 μg/mL HER3-blocking antibody or an isotype control antibody for 1 hour. In both assays, cells were plated in triplicate at a density of 100,000 cells per well either on a membrane or onto a growth factor–reduced Matrigel-coated membrane with 8 μm pores of a modified Boyden chamber (Schubert and Weiss) containing 500 μL serum-free medium. Conditioned NIH3T3 medium containing 100 ng/mL heregulin-β1 and 0.01% ascorbic acid served as a chemoattractant. The cells were allowed to migrate or invade for 20 or 24 hours, respectively. Migrated and invaded cells were stained by crystal violet, washed in PBS, and analyzed using a Zeiss Axiovert 300 microscope. For quantification, 10 random fields at least were counted per filter. The data are shown as mean ± SD. The apoptosis assay was done using a propidium iodide staining. Briefly, cells were serum starved in medium containing 1% FCS and afterward preincubated with either 10 μg/μL blocking antibody (clone 105.5) or an isotype control. After 72 hours, floating cells were collected and adherent cells were trypsinized. After centrifugation, cells were incubated for 2 hours in a propidium iodide buffer (0.1% sodium citrate, 0.1% Triton X-100, and 20 μmol/L propidium iodide) and subsequently subjected to flow cytometric analysis (Becton Dickinson Biosciences). Apoptotic cells were identified as the sub-G0 to G1 peak quantified using the CellQuest Pro Software (Becton Dickinson).

**HER family member expression in colon cancer cell lines**

To select a model system which is suitable for our investigation, we screened a panel of 5 colon cancer cell lines (DLD-1, LoVo, CaCO2, RKO, and T-84) for the protein expression levels of 3 members of the HER family, namely HER3, HER2, and EGF-R. HT-29 and HCT-116 colon cancer cell lines were tested previously (32) and considered as positive and negative control for HER3 expression, respectively (Fig. 2). A considerable difference by the HER3 expression was observed among the 5 tested cell lines. Whereas DLD-1 and T-84 cell lines are characterized by a very high to a high HER3 level, respectively, CaCO2 and LoVo express HER3 moderately. No detectable HER3 was observed in the RKO cell line. To further validate our results, basal phosphorylation levels of HER3 of the same cell lines were assessed (Supplementary Fig. S1). While HER2 expression levels vary from one cell line to the other, all tested cell lines showed moderate EGFR expression levels (Fig. 2).

**HER3 knockdown affects proliferation of colon cancer cell lines and interferes with activation of downstream targets**

To validate our clinical results, we focused on the function of the HER3 receptor tyrosine kinase in vitro, by testing its influence on diverse biologic processes including proliferation, motility, invasion, and survival. We therefore reasoned to downregulate HER3 in DLD-1, LoVo, CaCO2, and T-84 colon cancer cell lines by siRNA (Fig. 3A; Supplementary Figs. S4A and S5A).

First, we addressed the question whether HER3 could be involved by the regulation of colon cancer cell proliferation. As expected, depletion of HER3 strongly inhibited proliferation in all 4 tested cell lines (Fig. 3B; Supplementary Figs. S4B and S5B). In addition, HER3 knockdown significantly inhibited heregulin-β1–induced cell proliferation (Fig. 3B; Supplementary Figs. S4B and
S5B). To further characterize the molecular mechanism behind this growth inhibition, we checked expression levels of main proteins implicated in the regulation of the cell cycle before and after HER3 knockdown. As shown in Fig. 3C and Supplementary Figs. S4C and S5C, HER3 suppression lead to a significant decrease in cyclin B1 expression as well as to decreased Rb phosphor-ylation, suggesting that HER3 controls cell proliferation by interfering with key cell-cycle regulators.

We subsequently asked whether HER3 knockdown has an effect on known downstream substrates, namely, ERK1/2 and AKT, which are, respectively, effector proteins responsible for mitogen-activated protein kinase cascade activation and lipid signaling (27, 33). AKT activation as well as phospho-mTOR levels were impaired subsequent to HER3 knockdown in both heregulin-β1–stimulated and nonstimo-lated cells, indicating that HER3 may signal via the PI3K/AKT pathway in colon cancer cells (Fig. 3D; Supplementary Fig. S4D). Moreover, HER3-knockdown cells showed increased p27 protein expression levels in comparison with control cells (Fig. 3D; Supplementary Fig. S4D). In contrast, phospho-ERK remained unchanged (Fig. 3D; Supplementary Fig. S4D).

**HER3 knockdown induces a G₂-M cell-cycle arrest in colon cancer cell lines**

Because HER3 suppression by siRNA leads to inhibition of Rb phosphorylation as well as to decreased cyclin B1 protein expression levels, we asked whether the absence of HER3 could influence progression of the cell cycle. To address this question, we conducted a cell-cycle analysis and checked elements of the cell cycle before and subsequent to HER3 knockdown. Interestingly, significant increased amounts of cells by the G₂-M phase were observed in all 4 HER3-knockdown cells when compared with the controls (GL-2 siRNA as well as untransfected cells). Parallel to this, a shift in the G₁ and S-phases was detected (Fig. 4A and B).

Figure 1. HER3 confers poor prognosis in patients with colon cancer. A–E, immunohistochemical staining of HER3 in primary tumors of patients with colon cancer. A, low membranous HER3 expression (arrows). B, moderate membranous HER3 expression (arrows). C and D, strong membranous HER3 expression (arrows). E, frequencies of HER3 expression in primary colon carcinomas. Primary tumors (n = 110) were evaluated for HER3 expression. F, Kaplan–Meier curve for overall survival of patients with high and low HER3 expression levels (P = 0.0131).
respectively. As shown in Fig. 5A, proliferation, we used serum-starved conditions and monocyted LoVo cell lines in the presence or absence of siRNA targeting HER3 is required for colon cancer motility and invasion, breast cancers (14, 16, 29). To address the question, whether HER3 impact on migration and invasion.

**HER3 knockdown suppresses migration and invasion and induces apoptosis in colon cancer cell lines**

HER3 has been shown to be implicated in the regulation of several oncogenic processes, particularly, migration and invasion in different cancer types including lung skin and breast cancers (14, 16, 29). To address the question, whether HER3 is required for colon cancer motility and invasion, we conducted migration and invasion assays in DLD-1 and LoVo cell lines in the presence or absence of siRNA targeting HER3. To exclude the possibility of measuring inhibition of proliferation, we used serum-starved conditions and monitored migration and invasion after 20 and 24 hours, respectively. As shown in Fig. 5A, HER3 siRNA effectively abrogated migration of both cell lines. Furthermore, invasiveness of both DLD-1 and LoVo was markedly inhibited upon HER3 suppression (Fig. 5B). These results suggest a prominent role of HER3 in regulating migration as well as invasiveness of colon cancer cell lines.

To further characterize the role of HER3 in vitro, we asked whether HER3 downregulation by siRNA induces cell death in colon cancer cell lines. Interestingly, in line with previously published data in lung cancer cell lines which undergo apoptosis in the absence of HER3 (14), suppression of HER3 leads to a moderate induction of apoptosis which varies from one cell line to the other inside our model system (Fig. 5C; Supplementary Fig. S6). We next checked whether 5-fluorouracil, a common chemotherapeutic used for the treatment of patients with colon cancer, could increase the already obtained apoptotic effect upon HER3 knockdown. Importantly, HER3 inhibition synergizes with chemotherapy in apoptosis induction. Treatment of HER3-knockdown cells with 5-fluorouracil but not of control cells gave rise to a significant increase in the apoptosis rates of the treated cells, reaching about 45% and 32% for DLD-1 and LoVo cell lines, respectively (Fig. 5C). The same effect was also observed in both other colon cancer cells CaCO2 (~45%) and T-84 (~30%; Supplementary Figs. S4E and S5D). These results suggest that a combinatorial therapy with HER3-inhibitory and 5-fluorouracil–like drugs might be useful for the treatment of malignant colon cancer.

**Anti-HER3 monoclonal antibody blocks heregulin-β1–induced HER3 activation, inhibits colon cancer cell migration and invasion, and induces apoptosis in colon cancer cell lines**

To test the hypothesis whether HER3 could be considered as a potential target for colon carcinoma therapy, we analyzed the effects of an HER3 monoclonal–blocking antibody (clone 105.5), which specifically antagonizes the heregulin-β1 binding to HER3 in breast and skin cancer cell lines (16, 29). We therefore immunoprecipitated HER3 in cells treated with either HER3 monoclonal antibody (clone 105.5) or a control antibody and stimulated with heregulin-β1. We then assessed the phosphorylation of HER3 and the expression levels of the regulatory subunit of PI3K, the p85 protein. Remarkably, anti-HER3 monoclonal antibody interferes with the activation of heregulin-β1–induced activation of the HER3 receptor and its association with the PI3K subunit, p85 in DLD-1 and LoVo. However, inhibition was incomplete in the CaCO2 cell line (Fig. 6A). Similar to previous reports (16, 29), HER3 seemed to be degraded or internalized through the anti-HER3 monoclonal antibody in DLD-1 and LoVo colon cancer cell lines (Fig. 6A). Interestingly, the HER3-blocking antibody was able to block migration and invasion and to induce apoptosis in the DLD-1 and LoVo colon cancer cell lines (Fig. 6B–D), indicating that such antibodies may be effective for the treatment of patients with colon cancer. Taken together, these results have potential therapeutic significance of HER3 as a new promising target for colon cancer treatment.

### Table 1. Multivariate analysis of cancer-specific survival

<table>
<thead>
<tr>
<th>Variable</th>
<th>HR (95% CI)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (≥68 vs. ≤67)</td>
<td>1.72 (0.91–3.22)</td>
<td>0.09</td>
</tr>
<tr>
<td>Gender (male vs. female)</td>
<td>0.93 (0.47–1.81)</td>
<td>0.82</td>
</tr>
<tr>
<td>Tumor grade</td>
<td>0.89 (0.37–2.18)</td>
<td>0.80</td>
</tr>
<tr>
<td>Tumor location</td>
<td>1.75 (0.88–3.46)</td>
<td>0.11</td>
</tr>
<tr>
<td>Rectal vs. colon</td>
<td>3.95 (2.04–7.66)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>HER3 (high vs. low)</td>
<td>3.29 (1.28–8.45)</td>
<td>0.014</td>
</tr>
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Abbreviation: CI, confidence interval.

Surprisingly, the morphology of HER3-knockdown cells changed toward a flat appearance, whereas control transfected cells retained their compact cell shape (Supplementary Fig. S2). This observation prompted us to examine HER3 impact on migration and invasion.

![Figure 2](https://www.aacjrournals.org) Expression levels of EGFR, HER2, and HER3 in colon cancer cells. Equal amounts of protein lysates from T-84, DLD-1, LoVo, CaCO2, RKO, HT-29, and HCT-116 colon cancer cell lines were subjected to immunoprecipitation (IP) using a specific HER3 antibody as well as to Western blot (WB) analysis. HT-29 and HCT-116 were considered as a positive and a negative control, respectively. Representative immunoblots for EGFR, HER2, and HER3 are shown. Tubulin served as loading control.
Figure 3. HER3 knockdown inhibits colon cancer cell proliferation. A, Western blot analysis of HER3 and β-actin in DLD-1 and LoVo colon cancer cell lines after HER3 ablation. B, inhibition of DLD-1 and LoVo colon cancer cell proliferation by HER3 siRNA. The impact of HER3 knockdown on cell proliferation was shown in both unstimulated and heregulin-β1-stimulated cells. The growth curves were made as described in Materials and Methods. Data represent mean ± SD. **, significant, P < 0.05 (t test). C, HER3 knockdown induces changes in the expression and phosphorylation of key cell-cycle regulators, cyclin B1, and phospho-Rb. Western blot analyses are shown for phospho-Rb and cyclin B1, β-Actin served as a loading control. D, HER3 knockdown impairs AKT and mTOR activities in DLD-1 and LoVo colon cancer cell lines. Western blot analysis for HER3, phospho-AKT, p27, phospho-ERK1/2, and phospho-mTOR are shown. Tubulin served as a loading control.
Figure 4. HER3 knockdown induces a G2–M cell-cycle arrest in colon cancer cell lines. A, representative flow cytometric histograms of DLD-1, T-84, CaCO2, and LoVo cell lines. Forty-eight hours posttransfection, cell-cycle kinetics of HER3-knockdown cells and control cells were determined by propidium iodide staining. B, data represent means of triplicate experiments. *, significant, $P < 0.05$ (t test); **, highly significant, $P < 0.001$ (t test).
Discussion

Pseudokinases such as HER3 are emerging as crucial regulators of diverse cellular functions, despite lacking the ability to directly phosphorylate substrates (34). Recent studies highlighted HER3 as a fundamental signaling receptor involving the modulation of different biologic processes in a wide range of cancer types including pancreatic, breast, prostate, gastric, ovarian, and skin cancer (15, 16, 27, 35–37). In some of these tumors, HER3 expression was even shown to be correlated with poor prognosis (15–18). In addition, recent works show that tumors escape from EGFR- and HER2-targeted therapy by a rapid compensatory increase in HER3 expression and in a PI3K/AKT signaling pathway (30), suggesting that agents targeting HER3 could provide a novel and promising approach toward the treatment of such cancers.

HER3 represents a transmembrane receptor that is activated by ligand binding. Therefore, one might assume that the predominant localization of HER3 should be the cell membrane. Nevertheless, several publications using different anti-HER3 antibodies for staining of tumor samples showed a cytoplasmic rather than a membranous staining pattern for this receptor (1, 15). In our study, we detected a clear membranous localization of HER3 in all 110 analyzed paraffin-embedded specimens of primary colorectal tumors as well as a strong correlation of HER3 expression with overall survival of patients, establishing HER3 as a putative novel independent prognostic marker for colon cancer. This is of great importance because several therapeutic antibodies aimed at targeting the membrane-localized receptor are currently being tested in clinical trials and will hopefully be available as a treatment modality soon. Indeed, these results are in accordance with previous studies, where HER3

Figure 5. HER3 knockdown induces apoptosis and blocks migration and invasion of colon cancer cells. A, HER3 knockdown inhibits migration of DLD-1 and LoVo colon cancer cells. For quantification, migrated cells were fixed, stained, and counted. A total of at least 10 random microscopic fields were counted. The values for control cells were set to 100% and results are shown relative to controls. Data represent mean ± SD. B, HER3 knockdown blocks DLD-1 and LoVo colon cancer cell invasion. Quantification of invaded cells was done as described in (A). C, HER3 depletion by siRNA induces apoptosis in DLD-1 and LoVo colon cancer cell lines. The percentage of apoptotic cells was increased upon treatment of HER3-knockdown cells with increasing 5-fluorouracil concentrations (10 and 20 μmol/L). Data represent mean ± SD. *, significant, \( P < 0.05 \) (t test). **, highly significant, \( P < 0.001 \) (t test).
expression tightly correlated with poor survival of patients with colorectal cancer (38, 39). Nevertheless, further investigations concerning the HER3 status versus the genetic classification of the CRC tumors, namely, LOH, microsatellite instability, hereditary nonpolyposis colorectal cancer would be of interest to get further insights into the relevance of HER3 expression in different colon cancer subtypes.

To specifically address the function of HER3 in colon cancer development and progression, human colon cancer cell lines were analyzed by siRNA interference with HER3 expression. As described above, downregulation of HER3 induced a reduction in proliferation as well as a G2–M cell-cycle arrest in all 4 tested colon cancer cell lines. On the molecular signaling level, HER3 knockdown resulted in increased p27 expression levels. In addition, phosphorylation of Rb and cyclin B1 expression were reduced upon HER3 knockdown in comparison with the control cells. Indeed, these molecules are well established and known as essential cell-cycle regulators. Their modulation seemed to be the direct cause of the observed growth inhibition and the cell-cycle arrest in colon cancer cells.

HER3 downregulation in both heregulin-β1-stimulated and nonstimulated cells results in a reduction of the AKT phosphorylation (Fig. 3D; Supplementary Fig. S4D).
In fact, upregulation of p27 may be a direct consequence of the observed impairment of the AKT activity as AKT is known to trigger p27 degradation and cell-cycle progression (40–43). Furthermore, it is important to note that several already published reports have shown the well-established potential of HER3 to activate downstream PI3K/AKT pathway signaling by virtue of 6 consensus phosphotyrosine sites, which are absent in EGFR or HER2 (16, 28, 44–46). Interestingly, the impaired AKT activity shown in cells upon HER3 knockdown was accompanied by a reduction in the phosphorylation of mTOR at Ser2448, which is known to be mediated by the PI3K/AKT signaling pathway (47). Notably, HER3 ablation did not affect the ERK1/2, suggesting that inhibition of other downstream pathways seemed to be sufficient to block colon cancer cell proliferation. Taken together, our results suggest that HER3 expression and phosphorylation controls colon cancer cell proliferation majorly through the PI3K/AKT signaling pathway.

We subsequently checked the role of HER3 as a regulator of cell survival in colon cancer. Interestingly, HER3 depletion in all 4 tested colon cancer cell lines resulted in an induction of apoptosis, which varied form one cell line to another. Our observations are in fact in accordance with previous studies showing the involvement of the HER3 receptor in regulating cell survival. Indeed, Lee and colleagues showed that deletion of HER3 induced a tumor-specific apoptosis in mouse intestinal epithelium (48). In addition, HER3 downregulation in lung cancer cells led to a significant induction of apoptosis (14). Moreover, HER3 knockdown synergistically enhanced dacarbazine-induced apoptosis in melanoma cell lines (16). We next asked whether a combination of HER3 downregulation with chemotherapeutic drug treatment would increase cell death in our model system. To date, 5-fluorouracil is the frequently used chemotherapeutic for the treatment of patients with colon cancer. 5-Fluorouracil was also approved to be effective toward different colon cancer cell lines (49, 50). Interestingly, the treatment of colon cancer cells using increasing 5-fluorouracil concentrations upon HER3 downregulation resulted in increased rates of apoptosis, suggesting that blocking HER3 might prove effective in the treatment of malignant colon cancer.

Notably, established here for its first time is also the importance of HER3 in modulating migration and invasion of colon cancer cell lines. Both processes were markedly inhibited by HER3 siRNA interference in DLD-1 and LoVo cell lines. Indeed, stimulation of tumor migration and invasion appears to be an essential function of HER3 in some other model systems because HER3 downregulation abolished migration and invasion in melanoma and breast cancer cell lines, respectively (16, 29). The involvement of HER3 in regulating motility and migration was additionally shown in the A549 lung cancer cell line (14). It will be of importance to elucidate the exact role of HER3 in these processes and to identify factors, which mediate EGFR/HER3 responses during colon cancer metastasis (e.g., metalloproteinases).

Interestingly, HER3-knockdown cells display a shift in the cell morphology, which is characterized by the change of cells toward a flat and round appearance. We believe that HER3 knockdown shifted the cells toward an epithelial-like cell morphology. To address this hypothesis in more detail, additional experiments were carried out. We investigated changes in expression of the mesenchymal marker vimentin after HER3 downregulation in LoVo colon cancer cells as an example. Decreased expression levels of vimentin were observed by Western blot analysis and by immunofluorescence (Supplementary Fig. S3). Because these findings indicate HER3 as a potential regulatory factor for mesenchymal marker expression within colon cancer, it is possible that HER3 expression is linked to epithelial-to-mesenchymal transition (EMT), a common principle during colon cancer progression.

The use of blocking antibodies for the treatment of cancers overexpressing pseudokinases such as HER3 is promising, as the use of small-molecule inhibitors is thought to be inefficient in this case due to the absence of phosphotyrosine sites (51). We therefore treated human colon cancer cell lines using anti-HER3 monoclonal antibody, thereby testing the aptitude of HER3 to be considered as a novel target in colon cancer therapy. Our results indicate that an antibody directed against the extracellular domain of HER3 efficiently inhibits its phosphorylation after heregulin-β1 stimulation. Anti-HER3 monoclonal antibody accelerates the endocytosis of HER3, resulting from its clearance from the cell surface, and inhibits the activation of downstream effectors because the binding of p85, the regulatory subunit of PI3K, to HER3 was abrogated. Remarkably, an induction of apoptosis in DLD-1 and LoVo colon cancer was shown to be induced after the treatment of cells using the HER3-blocking antibody for the first time. Furthermore, migration and invasion were considerably reduced in antibody-treated cells when compared with controls. Indeed, our results are well in line with previous studies, which established the efficiency of the same blocking antibody toward HER3-mediated migration and migration/invasion in breast and skin cancer, respectively (16, 29). Taken together, previous as well as our present data indicate that anti-HER3 antibodies can inhibit HER3 signaling most likely through the PI3K/AKT pathway in breast, melanoma, and colon cancer, thereby blocking several cellular functions. It will be necessary in the future to test the efficacy of anti-HER3–blocking antibodies on colon cancer development and metastasis in preclinical animal models to further validate HER3 as a possible target for colon cancer therapy.

Collectively, our data confirm that HER3 emerges as an important determinant of colon cancer behavior as well as a possible novel target for drug design.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.
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