Anti-VEGF therapy induces ECM remodeling and mechanical barriers to therapy in colorectal cancer liver metastases

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The survival benefit of anti–vascular endothelial growth factor (VEGF) therapy in metastatic colorectal cancer (mCRC) patients is limited to a few months because of acquired resistance. We show that anti-VEGF therapy induced remodeling of the extracellular matrix with subsequent alteration of the physical properties of colorectal liver metastases. Preoperative treatment with bevacizumab in patients with colorectal liver metastases increased hyaluronic acid (HA) deposition within the tumors. Moreover, in two syngeneic mouse models of CRC metastasis in the liver, we show that anti-VEGF therapy markedly increased the expression of HA and sulfated glycosaminoglycans (sGAGs), without significantly changing collagen deposition. The density of these matrix components correlated with increased tumor stiffness after anti-VEGF therapy. Treatment-induced tumor hypoxia appeared to be the driving force for the remodeling of the extracellular matrix. In preclinical models, we show that enzymatic depletion of HA partially rescued the compromised perfusion in liver mCRCs after anti-VEGF therapy and prolonged survival in combination with anti-VEGF therapy and chemotherapy. These findings suggest that extracellular matrix components such as HA could be a potential therapeutic target for reducing physical barriers to systemic treatments in patients with mCRC who receive anti-VEGF therapy.

INTRODUCTION

Systemic chemotherapy is the main treatment option for patients with inoperable metastatic colorectal cancer (mCRC). The effectiveness of chemotherapy depends on the delivery of the drugs into the tumor, which in turn is dependent on tumor blood perfusion (1–4). There is increasing evidence that the solid stress generated by proliferating cells in a growing tumor mass can cause compression of blood vessels and reduced perfusion (5). Components of the extracellular matrix (ECM) play an important role in the solid stress–induced blood vessel collapse because they transmit the mechanical stress created by proliferating cells within the confined space of a tumor (6). Targeting the ECM components has therefore been suggested as a strategy to improve perfusion, drug delivery, and, ultimately, outcomes in patients with solid malignancies (3, 7).

The anti–vascular endothelial growth factor (VEGF) antibody bevacizumab in combination with chemotherapy is the current standard of care for mCRC, based on an overall survival improvement (8). This survival benefit, however, is modest, and the disease ultimately progresses (9). The underlying mechanisms of acquired resistance to antiangiogenic therapy remain unclear (7). In part, this is a result of the limited understanding of the effects of anti-VEGF therapy on the microenvironment of metastatic lesions. Recent preclinical studies have shown that antiangiogenic therapy increases collagen expression in primary tumors, as a consequence of increasing hypoxia (10, 11). The effect of antiangiogenic therapy on the expression of noncollagenous matrix components such as hyaluronic acid [also known as hyaluronan (HA)] or sulfated glycosaminoglycans (sGAGs) in metastatic lesions is not well studied. As an abundant and highly hydrated matrix molecule with negatively charged chains that resist compression, HA has gathered increasing attention as a biologically relevant and potentially targetable cause of vessel compression and poor drug delivery in desmoplastic tumors (12–15). Recently, liver metastases from pancreatic cancer have been reported to be desmoplastic with high concentrations of HA and collagen that correlated with patients’ survival (16). Here, we investigated the effects of antiangiogenic therapy on the composition of the ECM, both collagenous and noncollagenous, and blood perfusion as mechanisms of acquired resistance to antiangiogenic therapy in liver mCRC.

RESULTS

Bevacizumab increases HA expression in human CRC liver metastases

Given the lack of data on expression of HA in human liver mCRC, we first performed immunohistochemical analyses of surgical specimens from mCRC patients who underwent metastasectomy. We found higher expression of HA in the metastases compared to that of the uninvolved liver parenchyma, where HA expression was restricted to the perportal fields (fig. S1). Next, we examined the impact of preoperative...
treatment on HA deposition in 49 liver metastases resected from 43 patients (table S1). Although there was no difference in HA between patients with and without preoperative chemotherapy, we found significantly increased HA expression in liver mCRC tissues from patients treated with preoperative bevacizumab and chemotherapy ($P < 0.001$) (Fig. 1, A and B). To further confirm this potential effect of bevacizumab, we analyzed serial samples from patients who underwent multiple liver resections for CRC liver metastases and carried out intradividual comparisons of HA expression. These analyses confirmed the significant increase in HA expression after preoperative treatment including bevacizumab ($P = 0.024$, paired $t$ test), with relatively low intensity of staining in samples from the same patients who were resected at different time points without previous exposure to anti-VEGF therapy (Fig. 1, C and D).

**Anti-VEGF therapy alters mechanical properties of murine CRC liver metastasis**

Next, to investigate the mechanisms and consequences of increased HA expression after VEGF-targeted therapy, we used two syngeneic mouse models of liver mCRC (SL4 and CT26) (17, 18). The effectiveness of anti-VEGF therapy was different in these models. Whereas treatment with B20.4-1.1 [a VEGF-blocking antibody abbreviated as B20 from here onward (19)] significantly prolonged survival of mice bearing liver metastatic SL4 tumors (median survival, 14.25 versus 10.4 days; $P < 0.001$, log-rank test), the survival advantage in the CT26 model did not reach statistical significance (median survival, 13.5 versus 12 days; $P = 0.072$, log-rank test) (Fig. 2A). The macroscopic appearance of the metastatic lesions in the anti-VEGF treatment groups was different from that seen in the control groups and was characterized by a stiff texture, suggesting changes in the amount and/or composition of the ECM. We also found that the DNA content, normalized to wet weight, was significantly lower in SL4 ($P = 0.011$) and CT26 ($P = 0.023$) liver mCRCs of mice treated with B20, suggesting a shift in the cell-to-matrix ratio (fig. S2, A and B). To quantify the changes in the mechanical properties of liver mCRCs after anti-VEGF therapy, we performed stiffness measurements using unconfined compression tests of metastases harvested from animals treated with B20. These experiments confirmed a dose-dependent increase in tumor stiffness in SL4 ($P = 0.002$) and CT26 ($P < 0.0001$) liver mCRC models (Fig. 2B). In addition, a recently developed method to measure growth-induced...
solid stress (6) revealed significantly higher solid stress in anti-VEGF–treated mCRCs. The normalized mean tumor opening—a measure of solid stress—increased from 0.690 to 1.506 for SL4 tumors ($P = 0.018$) and from 1.830 to 5.884 for CT26 tumors ($P = 0.019$) (Fig. 2C). Anti-VEGF therapy caused >80% reduction in tumor perfusion (Fig. 2D). Together, these data indicate that anti-VEGF therapy (at 5 mg/kg) alters the mechanical properties of liver metastases by inducing tumor desmoplasia.

**HA and sGAG in colorectal liver metastases increase after anti-VEGF treatment**

To evaluate the effect of anti-VEGF therapy on the ECM, we first measured the relative abundance of the major ECM components. In line with the clinical findings of increased HA expression in human liver mCRCs after bevacizumab treatment, we found a threefold increase of HA in SL4 (0.503 ± 0.035 versus 1.766 ± 0.233 μg HA/mg tissue; $P < 0.0001$) and CT26 (0.055 ± 0.0108 versus 0.143 ± 0.014 μg HA/mg tissue; $P < 0.0001$) liver mCRCs in mice (Fig. 3A). In addition, the expression of CD44, the HA receptor, was increased in metastatic lesions of SL4 ($P = 0.008$) and CT26 ($P = 0.005$) tumors after anti-VEGF therapy (fig. S3, A and B). Moreover, we found a twofold increase in sGAG expression after anti-VEGF therapy in both mouse models (SL4: 0.231 ± 0.022 versus 0.43 ± 0.044 μg sGAG/mg tissue; $P = 0.0005$; CT26: 0.149 ± 0.021 versus 0.277 ± 0.028 μg sGAG/mg tissue; $P = 0.001$) (Fig. 3B). The increased expression of sGAG was then confirmed in liver mCRCs in patients treated with preoperative chemotherapy with and without bevacizumab (fig. S4). The increase in collagen deposition was less pronounced and reached statistical significance only in the SL4 model ($P = 0.01$) (Fig. 3C), a finding consistent with the data from patients with liver mCRCs after preoperative chemotherapy with and without bevacizumab (20). To rule out the possibility that the changes in the ECM are off-target effects related to anti-VEGF therapy, we treated non–tumor-bearing mice with B20 for 3 weeks. Histological analysis did not reveal obvious parenchymal changes in the liver (fig. S5A). Moreover, biochemical analysis of the liver tissue did not show major differences between the groups with respect to HA and sGAG abundance (fig. S5, B and C). We then sought to correlate the stiffness of the liver mCRCs with the presence of specific ECM components. We found a strong correlation between stiffness and tumor concentration of HA (SL4: $r = 0.72$; $P < 0.0001$; CT26: $r = 0.554$; $P < 0.0001$) or sGAG (SL4: $r = 0.665$; $P < 0.0001$; CT26: $r = 0.524$; $P = 0.0002$) but no association with collagen content (Fig. 3D).
Inflammatory cell depletion does not alter HA production after anti-VEGF therapy

Immune cells, specifically CD11b+Gr1+ myeloid-derived suppressor cell (MDSC) populations such as Ly6C\textsuperscript{hi} inflammatory monocytes (IMs), play a role in liver fibrosis, tumor progression, and resistance to antiangiogenic therapy, including primary liver tumors (11, 21–24). To evaluate the potential role of these cell populations in ECM deposition after anti-VEGF therapy, we performed flow cytometry analysis of tumor tissues from mice treated with B20 or IgG. The results demonstrated a significant influx of Ly6C\textsuperscript{hi} IMs as well as metastasis-associated neutrophils (MANs) in SL4 liver mCRCs, at 3 days (Ly6C\textsuperscript{hi} IMs: 0.384 ± 0.042 versus 0.192 ± 0.022; MANs: 0.22 ± 0.02 versus 0.176 ± 0.018; Student’s t test) after initiation of anti-VEGF therapy (Fig. 4, A and B). These results were confirmed in the CT26 liver mCRCs (Fig. 4E). Flow cytometric analysis of the spleen tissue—a “reservoir” for tumor-associated monocytes and neutrophils (25, 26)—and peripheral blood cells showed that increased counts of these cells in metastases and in peripheral blood associated with lower counts in the spleen. These data suggested a release of these cell populations from the spleen into the circulation and the mCRC tissues (Fig. 4, B and C). There were no significant differences in the cell numbers to antiangiogenic therapy, including primary liver tumors (11, 21–24), and the anti-Ly6G antibody reduced abrogation of increased tumor infiltration by MDSC in liver mCRC response to anti-VEGF therapy (Fig. 4F). We did observe a decrease in collagen in Liver metastases from Ccr2\textsuperscript{−/−} mice had an 83% reduction in Ly6C\textsuperscript{hi} IM compared to WT mice receiving VEGF-targeted therapy (P = 0.009, Student’s t test), whereas combined treatment with B20 and the anti-Ly6G antibody reduced MAN by 85% compared to B20 alone (P = 0.002, Student’s t test). Furthermore, depletion of one MDSC population did not result in compensatory recruitment of the other cell type (Fig. 4D). Biochemical analysis of liver mCRCs collected from these mice showed persistent enrichment of HA in mice treated with B20 despite depletion of Ly6C\textsuperscript{hi} IMs (0.371 ± 0.132 versus 1.941 ± 0.347 μg HA/mg tissue; P = 0.004, Student’s t test) or MANs (0.592 ± 0.099 versus 2.445 ± 0.432 μg HA/mg tissue; P = 0.002, Student’s t test) (Fig. 4E). Similarly, depletion of Ly6C\textsuperscript{hi} IMs (0.192 ± 0.022 versus 0.384 ± 0.042 μg sGAG/mg tissue; P = 0.001, Student’s t test) or MANs (0.176 ± 0.018 versus 0.393 ± 0.049 μg sGAG/mg tissue; P = 0.002, Student’s t test) did not abrogate the increased deposition of sGAG after anti-VEGF therapy (Fig. 4F). We did observe a decrease in collagen in Ccr2\textsuperscript{−/−} mice (Fig. 4G), a finding consistent with the role of Ly6C\textsuperscript{hi} IMs in the pathogenesis of liver fibrosis (24). Collectively, our results show that the accumulation of HA or sGAG in liver mCRCs after anti-VEGF therapy is independent of the increased tumor infiltration by MDSC populations.
Angiotensin II receptor 1 deletion does not affect HA expression in mCRC after anti-VEGF therapy

The angiotensin II receptor 1 (AT1) signaling pathway is a relevant mediator of ECM deposition through transforming growth factor–β (TGF-β) activation and a potential target to decrease tumor desmolasis (27, 28). Thus, we next investigated the role of AT1 in tumor stiffness and increased deposition of noncollagenous matrix after anti-VEGF therapy of liver mCRCs. To this end, we generated SL4 liver metastases in angiotensin II type 1a receptor knockout (Agrt1a−/−) mice, measured tumor stiffness, and analyzed the ECM composition after treatment with B20 or IgG. We found a significant increase in stiffness after anti-VEGF therapy in liver mCRCs in Agrt1a−/− mice (1.11 ± 0.23 versus 5.93 ± 0.93 kPa; P = 0.0002, Student’s t test) (fig. S8A). Similarly, we observed a significant increase in HA (0.49 ± 0.036 versus 2.14 ± 0.57 μg HA/mg tissue; P = 0.008, Student’s t test) and sGAG (0.23 ± 0.018 versus 0.40 ± 0.044 μg sGAG/mg tissue; P = 0.005, Student’s t test) (fig. S8, B and C) and no significant change in collagen expression (fig. S8D). In line with these data, the concentration of TGF-β was either decreased (in SL4 tumors, P = 0.028, Student’s t test) or not changed (in CT26 tumors, P = 0.15, Student’s t test) after anti-VEGF therapy (fig. S9, A and B). Collectively, these data indicate that the abnormal deposition of HA and GAGs after anti-VEGF therapy in liver mCRCs is independent of the AT1 pathway.

Fig. 4. MDSCs do not increase noncollagenous matrix deposition after anti-VEGF therapy. (A) Representative flow cytometry plot presenting the influx of CD45+CD11b+Ly6C+ monocytes and CD45+CD11b+Ly6G+ neutrophils into SL4 liver metastases after anti-VEGF therapy. FITC, fluorescein isothiocyanate. (B) Fluorescence-activated cell sorting (FACS) analysis of Ly6C+ IMs and MANs in SL4 liver metastases grown in C57BL/6 WT mice after 3 days (Ly6C+ IMs, **P = 0.016; neutrophils, **P = 0.024, Student’s t test) and 6 days (Ly6C+ IMs, **P = 0.003; neutrophils, **P = 0.005, Student’s t test) of treatment with IgG or B20 (n = 7 to 10 per group). (C) FACS analyses of the blood (day 3: Ly6C+ IMs, **P = 0.017; neutrophils, **P = 0.03; day 6: Ly6C+ IMs, **P = 0.018; neutrophils, **P = 0.045, Student’s t test) and spleen (day 3: Ly6C+ IMs, **P = 0.037; neutrophils, **P = 0.03; day 6: Ly6C+ IMs, **P = 0.025; neutrophils, P = 0.21, Student’s t test) compartments of C57BL/6 WT mice bearing SL4 liver metastases after 3 and 6 days of treatment with IgG or B20 (n = 5 to 9 per group). (D) FACS analysis of Ly6C+ IMs and neutrophils in SL4 liver metastases grown in C57BL/6 WT mice after 7 days of treatment with IgG or B20 with or without anti-Ly6G therapy (5 mg/kg every 2 days), in Ccr2−/− mice after 7 days of treatment with IgG or B20 (Ly6C+ IMs, **P = 0.015; neutrophils, **P = 0.013, one-way ANOVA) with or without anti-Ly6G therapy (5 mg/kg every 2 days) (Ly6C+ IMs, **P = 0.014; neutrophils, **P = 0.08, one-way ANOVA), or in Ccr2−/− mice after 7 days of treatment with IgG or B20 (Ly6C+ IMs, **P = 0.03; neutrophils, **P = 0.001, one-way ANOVA) (n = 4 to 9 per group). The number of Ly6C+ IMs in liver mCRCs was significantly decreased in Ccr2−/− mice as compared with WT mice under IgG (**P = 0.016) or B20 treatment (**P = 0.009). On the other hand, anti-Ly6G antibody significantly decreased MANs under IgG (**P = 0.016) or B20 (**P = 0.002) treatment. (E to G) Quantification of HA concentration by ELISA (IgG versus B20, **P = 0.003; IgG versus B20 in Ccr2−/− mice, **P = 0.005; IgG versus B20/anti-Ly6G, ***P < 0.0001, one-way ANOVA) (E), sGAG concentration by DMMB assay (IgG versus B20, **P = 0.005; IgG versus B20 in Ccr2−/− mice, **P = 0.015; IgG versus B20/anti-Ly6G, **P = 0.013, one-way ANOVA) (F), and collagen concentration by hydroxyproline assay (IgG versus B20, P = 0.67; IgG versus B20 in Ccr2−/− mice, P = 0.68; IgG versus B20/anti-Ly6G, P = 0.97; one-way ANOVA) (G) in SL4 liver metastases treated with IgG or B20 after depletion of Ly6C+ IMs (Ccr2−/− mice) or MANs (anti-Ly6G antibody) (n = 7 to 10 per group). B20 treatments (5 mg/kg): on day 0 for 3-day experiments and on day 0 and day 3 for 6- and 7-day experiments. Data are shown as means ± SEM; **P = 0.05, ***P < 0.01, and ****P < 0.001 as compared to corresponding controls.
Fig. 5. Increased HA deposition after anti-VEGF therapy in colorectal liver metastases is mediated by hypoxia. (A and B) Representative immunohistochemistry images of SL4 liver metastases (A) and quantification of microvessel density (CD34 staining) in SL4 and CT26 liver metastases grown in C57BL/6 and BALB/c WT mice after 3 days (SL4, ***P < 0.0001; CT26, *P = 0.01, Student’s t test) and 6 days (SL4, **P = 0.001; CT26, **P < 0.0001, Student’s t test) of treatment with IgG or B20. Scale bar, 100 μm (n = 6 to 8 per group). (C and D) Representative immunohistochemistry images of hypoxic area (staining for pimonidazole adducts) of SL4 liver metastases (C) and quantification of hypoxic area fraction in SL4 and CT26 liver metastases grown in C57BL/6 and BALB/c WT mice after 3 days (SL4, **P = 0.009; CT26, *P = 0.026, Student’s t test) and 6 days (SL4, **P = 0.005; CT26, *P = 0.037, Student’s t test) (n = 6 to 8 per group) (D). (E) Quantification of HA concentration by ELISA after 3 days (SL4, P = 0.153; CT26, P = 0.542, Student’s t test) and 6 days (SL4, **P = 0.009; CT26, **P = 0.006, Student’s t test) of treatment (top), sGAG concentration by DMMB assay after 3 days (SL4, *P = 0.011; CT26, P = 0.984, Student’s t test) and 6 days (SL4, *P = 0.014; CT26, **P = 0.008, Student’s t test) of treatment (middle), and collagen concentration by hydroxyproline assay after 3 days (SL4, P = 0.069; CT26, P = 0.412) and 6 days (SL4, *P = 0.028; CT26, P = 0.575, Student’s t test) of treatment (bottom) with IgG or B20 in SL4 and CT26 liver metastases. (F) Immunofluorescence staining demonstrating colocalization of HA expression with hypoxic areas in SL4 liver metastases treated with B20 for 7 days (***P = 0.0003, Student’s t test) (n = 8 per group). Scale bar, 100 μm. (G) Immunofluorescence staining demonstrating an increase in matrix-producing α-SMA+/collagen-I+ cells in SL4 liver metastases after anti-VEGF therapy (*P = 0.043, Student’s t test) (n = 6 to 8 per group). Scale bar, 100 μm. (H) Hypoxia increases HA expression in human HSCs. Cells were cultured in normoxic (21% O2) versus hypoxic conditions (1% O2) for 48 hours (**P = 0.003, Student’s t test). Scale bar, 100 μm. B20 treatments (5 mg/kg): on day 0 for 3-day experiments and on day 0 and day 3 for 6- and 7-day experiments. All data are shown as means ± SEM; *P < 0.05, **P < 0.01, and ***P < 0.001 as compared to corresponding controls. DAPI, 4′,6-diamidino-2-phenylindole.
Targeting HA increases perfusion and improves efficacy of chemotherapy in liver metastases after anti-VEGF therapy

Enzymatic targeting of HA improves vascular function and perfusion in pancreatic cancer. To investigate whether depletion of HA can prevent the changes induced by anti-VEGF therapy, we treated mice with B20 with or without intravenous administration of a polyethylene glycol conjugated (PEGylated) hyaluronidase (PEG-HAse). Treatment with PEG-HAse in combination with B20 resulted in a 74% reduction of HA synthesis by matrix-producing HSCs in SL4 liver mCRCs after treatment with B20 (P = 0.043, Student’s t test) (Fig. 5G). To confirm that hypoxia mediates HA synthesis in HSCs, we carried out in vitro studies using human HSCs cultured in normoxic versus hypoxic conditions for 48 hours. Hypoxia caused a 4.5-fold increase in HA expression in human HSCs (P = 0.003, Student’s t test) (Fig. 5H). Collectively, these results indicate that increased hypoxia is the likely driving stimulus for HA production by activated HSCs after anti-VEGF therapy. On the basis of the spatiotemporal analyses, hypoxia induced by anti-VEGF therapy appears to be the initiating event in this context. Then, resultant aggravation of desmoplasia compromises tumor perfusion further and induces a vicious cycle of hypoxia, desmoplasia, and immunosuppression.
Although this confirmed this study, chemotherapy and anti-VEGF therapy modestly prolonged survival.

Our study has several limitations. Depletion of HA in addition to chemotherapy and anti-VEGF therapy modestly prolonged survival. Although this confirmed this study’s hypothesis, the results of this animal experiment should be validated in a controlled clinical trial designed to evaluate whether HA depletion can translate into a survival benefit in liver mCRC patients when using clinically relevant doses from phase 1b trials. On the basis of recent reports, HA depletion appeared more effective in patients with tumors with high baseline amounts of HA. We found a substantial variability in the increase in HA expression in human liver mCRC samples after anti-VEGF therapy. Although our study serves as a proof of principle that preventing anti-VEGF treatment–induced HA deposition could improve the efficacy of systemic therapy, the importance of this mechanism versus other mechanisms of acquired resistance remains to be determined in patients. It also remains to be seen whether alternative targets within the ECM can further improve the effects of systemic therapy in these patients. For example, direct targeting of HSCs (or metastasis-associated fibroblasts), the main source of ECM components within liver mCRCs, may offer a therapeutic strategy. Treatment with vitamin D receptor ligands might be another strategy to reduce or prevent the activation of HSCs.

In conclusion, our results show that anti-VEGF therapy at the dose used here and in the clinic up-regulates the expression of HA in liver mCRC both in mouse models and in patient samples. This may be a mechanism of acquired resistance in this setting because depletion of HA improved perfusion of liver mCRC in mice and their response to systemic chemotherapies. Thus, targeting the noncollagenous ECM is a potential strategy to enhance the efficacy of systemic treatments for mCRC patients.

MATERIALS AND METHODS
Study design
The objective of the present study was to evaluate the remodeling of the ECM and its clinical relevance in colorectal liver metastases after a VEGF-targeted therapy. The sample sizes of the experiments were selected on the basis of previous experience. Data collection was stopped at a priori defined time points. Animal experiments were performed in a confirmatory fashion with an a priori hypothesis without repetition. In vitro experiments were carried out in triplicate. Experiments were carried out in an unblinded fashion except for analyses of immunohistochemistry images.

Patient samples
Patient samples were obtained from the Heidelberg University Hospital. Surgical specimens of patients who underwent liver resection for colorectal liver metastases without preoperative chemotherapy, after preoperative chemotherapy without bevacizumab, or after preoperative chemotherapy with bevacizumab were analyzed. Analysis of human samples was in line with the Declaration of Helsinki. Collection of patient samples for scientific purposes was approved by the local ethics committee (323/2004), and written informed consent was obtained.

Cell and animal models
The SL4 mouse CRC cells were a gift from T. Irimura (17). The mouse CRC cell line CT26 was purchased from the American Type Culture Collection (catalog #CRL-2638). HSCs were purchased from ScienCell (catalog #5300). To model liver metastasis, the spleen was split into two...
sectors, and $1 \times 10^5$ cells were injected into the distal caudal sector, which was then resected. The other hemispleen remained in place. Tumor burden was assessed by measuring blood concentration of *Gaussia* luciferase (Gluc) from Gluc-transduced tumors (73, 74) or using a high-frequency ultrasound imaging system (VisualSonics). Mice were randomly assigned to the treatment groups, and treatments were initiated after the development of macroscopic liver metastases (~8 to 12 days after injection). See the Supplementary Materials and Methods for more details.

### Treatments
The anti-VEGF monoclonal antibody B20.4-1.1 (Genentech) was administered by intraperitoneal injection twice a week at 5 or 1 mg/kg. For neutrophil depletion, an anti-Ly6G antibody (clone RB6-8C5) was administered intraperitoneally every 2 days at a dose of 5 mg/kg. PEG-HAse (see the Supplementary Materials and Methods) was administered intravenously twice a week or 24 hours before administration of chemotherapy at a dose of 4.5 mg/kg (43). 5-FU chemotherapy was administered intravenously twice a week at a dose of 50 mg/kg.

### Histochemistry
Frozen blocks were cut at a thickness of 20 μm for immunofluorescence staining for α-SMA, collagen-I, HA, and hypoxia. Whole-tumor mosaic images were obtained from each sample with an Olympus (FV1000) confocal laser-scanning microscope. Paraffin blocks were cut at a thickness of 5 μm and stained with hematoxylin and eosin, CD34, CD44, and HA. For hypoxia staining, pimonidazole hydrochloride (60 mg/kg) (Hypoxyprobe) was injected intraperitoneally 60 min before tissue collection. For perfusion measurement, Hoechst 33342 (Sigma) was administered by portal infusion 5 min before tumor tissue collection (31). Image analyses were carried out in an automated fashion using a custom algorithm in MATLAB (MathWorks). See the Supplementary Materials and Methods for more details.

### Cytometry
Tissue samples from tumors, spleen, and bone marrow were digested and filtered through 70- and 40-μm cell strainers. Single cells were stained with CD45, CD11b, Ly6G, and Ly6C and analyzed using an LSR II flow cytometer (Becton Dickinson). See the Supplementary Materials and Methods for more details.

### Biochemical assays
sGAG content in finely dispersed tissues was determined by the Dimethylmethylene Blue Assay (DMMB) (75). Total collagen content was determined by measuring hydroxyproline content of the hydrolysate samples (76). Mouse HA and TGF-β1 were quantified using ELISA kits (R&D Systems). See the Supplementary Materials and Methods for more details.

### Physical parameters
The stiffness (Young’s modulus) of tumors was determined by unconfined compression tests (77). Solid stress was determined using a recently proposed method (6). In line with this method, the normalized tumor opening was used as a readout for growth-induced stress. See the Supplementary Materials and Methods for more details.

### Statistical analysis
Data are presented as means ± SEM and compared using Student’s *t* test, one-way ANOVA, or two-way ANOVA when appropriate.

Survival was estimated by Kaplan-Meier curves and compared using the log-rank test. All tests were two-sided. Statistical analyses were carried out using GraphPad Prism software. A *P* value of less than 0.05 was considered statistically significant.

## Supplementary Materials

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Materials and Methods

Fig. S1. Expression of HA is increased in CRC liver metastases compared to liver parenchyma. See the Supplementary Materials and Methods for more details.

Fig. S2. DNA content in murine CRC liver metastases is decreased after anti-VEGF therapy. See the Supplementary Materials and Methods for more details.

Fig. S3. CD44 expression is increased in liver metastases after anti-VEGF therapy. See the Supplementary Materials and Methods for more details.

Fig. S4. Bevacizumab increases sGAG expression in human CRC liver metastases. See the Supplementary Materials and Methods for more details.

Fig. S5. Anti-VEGF therapy does not alter ECM expression in healthy liver parenchyma. See the Supplementary Materials and Methods for more details.

Fig. S6. Anti-VEGF therapy results in recruitment of MDSCs into CT26 liver metastases. See the Supplementary Materials and Methods for more details.

Fig. S7. Anti-VEGF therapy does not alter IM and neutrophil counts in the bone marrow. See the Supplementary Materials and Methods for more details.

Fig. S8. Anti-VEGF therapy does not increase TGF-β content in murine CRC liver metastases. See the Supplementary Materials and Methods for more details.

Fig. S9. Anti-VEGF therapy does not alter IM and neutrophil counts in the bone marrow. See the Supplementary Materials and Methods for more details.

Fig. S10. Microvessel density is decreased, and hypoxia is increased in CT26 liver metastases after anti-VEGF therapy. See the Supplementary Materials and Methods for more details.

Fig. S11. Treatment with PEG-HAse lowers HA content in SL4 liver metastases. See the Supplementary Materials and Methods for more details.

### References and Notes


15. A. Rahbari, V. S. Gnaneswaran, C. Liu, S. Bardeesy, L. L. Munn, R. K. Jain, Compressi...


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Anti-VEGF therapy induces ECM remodeling and mechanical barriers to therapy in colorectal cancer liver metastases
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Editor's Summary

**Stiff resistance to cancer therapy**
Antiangiogenic therapy with drugs that block vascular endothelial growth factor (VEGF) signaling to inhibit formation of new blood vessels in tumors is commonly used in colorectal cancer. Unfortunately, the effects of this therapy usually do not last for long, and a study by Rahbari et al. shows why this might be the case. The authors found that VEGF inhibition increased the stiffness of colorectal cancer liver metastases, making them more difficult to treat with chemotherapy. In a mouse model, the researchers were able to overcome this difficulty by using an enzyme to degrade a component of the extracellular matrix in liver metastases, suggesting that the matrix may be a target for future cancer therapies.

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