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Clinical Cancer Research

Heterogeneous Blood–Tumor Barrier Permeability Determines Drug Efficacy in Experimental Brain Metastases of Breast Cancer

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Abstract

Purpose: Brain metastases of breast cancer appear to be increasing in incidence, confer significant morbidity, and threaten to compromise gains made in systemic chemotherapy. The blood–tumor barrier (BTB) is compromised in many brain metastases; however, the extent to which this influences chemotherapeutic delivery and efficacy is unknown. Herein, we answer this question by measuring BTB passive integrity, chemotherapeutic drug uptake, and anticancer efficacy *in vivo* in two breast cancer models that metastasize preferentially to brain.

Experimental Design: Experimental brain metastasis drug uptake and BTB permeability were simultaneously measured using novel fluorescent and phosphorescent imaging techniques in immune-compromised mice. Drug-induced apoptosis and vascular characteristics were assessed using immunofluorescent microscopy.

Results: Analysis of over 2,000 brain metastases from two models (human 231-BR-Her2 and murine 4T1-BR5) showed partial BTB permeability compromise in greater than 89% of lesions, varying in magnitude within and between metastases. Brain metastasis uptake of ^{14}C-paclitaxel and ^{14}C-doxorubicin was generally greater than normal brain but less than 15% of that of other tissues or peripheral metastases, and only reached cytotoxic concentrations in a small subset (~10%) of the most permeable metastases. Neither drug significantly decreased the experimental brain metastatic ability of 231-BR-Her2 tumor cells. BTB permeability was associated with vascular remodeling and correlated with overexpression of the pericyte protein desmin.

Conclusions: This work shows that the BTB remains a significant impediment to standard chemotherapeutic delivery and efficacy in experimental brain metastases of breast cancer. New brain permeable drugs will be needed. Evidence is presented for vascular remodeling in BTB permeability alterations. *Clin Cancer Res; 16(23); 5664–78. ©2010 AACR.*

Historically, brain metastases occurred in 10% to 20% of patients with disseminated breast cancer after the development of systemic lung, liver, and bone metastases. In such patients, treatment has been primarily palliative, with brain metastases rarely being the cause of death (1, 2). In recent years, however, the rate of brain metastasis has increased, approaching or exceeding 35% in subpopulations of metastatic breast cancer patients, particularly those with Her2$^+$ or "triple-negative" (estrogen and progesterone receptor negative, Her2 normal) tumors (3–5). The causes for this increase may be multiple, including improved systemic therapy, more frequent imaging, and the "sanctuary site" status of the brain. The net effect is that the patient experience is changing (6), with brain metastases more commonly presenting in patients who are responding to systemic therapy or have stable disease, and patients are succumbing to brain metastases (7). Clearly, a proportion of breast cancer patients are doing well systemically when brain metastases occur and need effective treatments for central nervous system (CNS) disease.

Current therapy for brain metastases of breast cancer involves radiation and surgery (1, 2). Stereotactic radiosurgery delivers a large dose of radiation to a defined brain lesion, whereas whole-brain radiotherapy irradiates the entire brain to treat multiple metastases and prevent the outgrowth of occult micrometastases. Surgery can remove one to several lesions in favorable locations. Steroids are used to control edema. The role of chemotherapy has been limited (8), as clinical trials of standard breast

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Translational Relevance

Brain metastases are prevalent in lung and breast cancers and melanoma. In metastatic breast cancer, the incidence of brain metastases approaches 35% of $Her2^+$ or triple-negative patients. Brain metastases are considered a "sanctuary site," yet comprehensive quantitative data on blood–tumor barrier (BTB) permeability to drugs are lacking. Here, we use two models of brain metastases of breast cancer to show that most metastases exhibit some increased BTB permeability; permeability is poorly correlated with lesion size, and only ~10% of lesions with the highest permeability exhibited cytotoxic responses to paclitaxel or doxorubicin. The data indicate that the BTB remains sufficiently intact in most experimental brain metastases to significantly impair drug delivery and reinforces the need for brain-permeable molecular therapeutics. Finally, we report that permeable brain metastases exhibit distinct BTB remodeling, in particular, an overexpression of the pericyte protein desmin, suggesting a first molecular target to modify permeability.

cancer drugs have provided disappointing results (9–11). Similar findings occur with other cancer histologies that metastasize to brain (12). Multiple strategies have been explored with limited success to improve brain metastasis chemotherapy, including combination with radiation, novel formulations, direct administration into the CNS, and targeted vascular disruption (8, 13). Both disease progression and treatments cause significant patient morbidity, including cognitive defects.

One of the reasons listed for the failure of brain chemotherapy is presence of the blood–brain barrier (BBB), which is located at the brain vascular endothelium (14). The BBB has low passive paracellular permeability and expresses high levels of active efflux drug transporters, which together limit brain exposure for many anticancer agents (15, 16). Included in this are two of the most widely used breast cancer chemotherapeutics, paclitaxel and doxorubicin, which are excluded from brain by BBB P-glycoprotein efflux transport (17–20).

The BBB is frequently impaired in brain metastases, creating the blood–tumor barrier [BTB; (21)]. The extent to which this compromise impacts CNS chemotherapy has been controversial for more than 30 years (14, 22–28). Many, but not all, brain metastases display elevated BTB permeability, as shown by MRI contrast enhancement to electron-dense tracers (1, 21). However, quantitative information is sparse on the relationship between BTB breakdown and chemotherapeutic drug delivery and activity in brain metastases. Few measurements have been made of chemotherapeutic drug exposure to brain metastases in humans or experimental animals (15, 29–31). The database is somewhat better for primary brain tumors (26, 29, 30, 32–38), but most drug penetration data are from studies of normal brain. Animal studies of drug distribution in brain metastases have been limited by nonphysiologic tumor models involving direct intracerebral tumor cell injection and by analytic methods that fail to capture the full heterogeneity of drug distribution within brain lesions. Furthermore, no studies have correlated drug levels in brain metastases with BTB passive permeability, transporter expression, and direct tumor cytotoxic effect.

Herein, we explore these questions using two recently established experimental models of brain metastasis that arise from the systemic circulation (39, 40). One involves the brain-colonizing subline (231-BR) of the metastatic triple-negative MDA-MB-231 human breast cancer cell line, which was isolated by repeated cycles of intracardiac injection and harvesting from brain metastases (40, 41). This model, when compared with human brain metastases of breast cancer, was found to have equivalent rates of proliferation and apoptosis and a prominent neuroinflammatory response (42). Furthermore, 231-BR brain metastases are contrast enhancing by MRI (43), supporting the relevance of this model to human disease. In this study, we have used a Her2 transfectant of 231-BR expressing enhanced green fluorescent protein (eGFP). This transfectant was chosen because it produced greater numbers of brain metastases than the parent cell line (40). The second model was derived using the murine 4T1 mammary breast cancer cell line (44). Novel quantitative fluorescent and phosphorescent imaging techniques were used with these models to assess the patency of the BTB to passive permeability markers and the degree of uptake of radiolabeled chemotherapeutic drugs. Results were then correlated, in the same lesions, with cleaved caspase-3 staining as a molecular marker of drug-induced apoptosis. Further drug efficacy was tested in a 4-week experimental brain metastasis assay. This integrated approach allowed us to address three important questions: a) To what extent does brain metastasis drug distribution correlate with BTB-induced changes in integrity? b) What level of brain metastasis drug exposure is associated with chemotherapeutic effect? and c) Do changes in BTB integrity between metastases correlate with BTB architecture, such as histologic structure, vascular density (angiogenesis), or pericyte expression?

Materials and Methods

Experimental metastasis assays

Female NuNu mice were anesthetized with isofluorane and inoculated with either breast cancer cell line (231-BR-Her2: 1.75×10^5 or 4T1-BR5: 5×10^4) in the left cardiac ventricle (Supplementary Fig. S1). Tumors seeded the brain and developed over 2 to 6 weeks until neurologic symptoms appeared. All experiments were conducted in accordance with approved animal use protocols.

Tracer or drug administration

Animals were anesthetized with ketamine/xylazine and administered Texas Red dextran (3 or 70 kDa, 1.5 mg per

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animal; Invitrogen) and/or ^{14}C-AIB (25 μC_i per animal; American Radiolabeled Chemicals), ^{14}C-paclitaxel (25 μC_i per animal, 10 mg/kg in Taxol formulation; Moravek), ^{14}C-doxorubicin (12.5 μC_i per animal, 6 mg/kg; GE Healthcare), or ^{14}C-dextran (70 kDa, 5 μC_i per animal; Moravek) into the femoral vein (Supplementary Fig. S1). Tracers circulated for 2 to 480 minutes, during which time blood samples ($n \leq 5$) were periodically collected to map the time course of blood exposure (45, 46). In some experiments, indocyanine green (1.5 mg per animal; Sigma) was injected intravenously 1 minute prior to death as a near-infrared marker of vascular density (47, 48). At the end of the circulation period, animals were euthanized and brain was removed from the skull (<30 seconds) and flash frozen in isopentane (−65°C). In most experiments, residual intravascular tracer was washed out of brain by cardiac perfusion (5–10 mL/min) for 30 to 60 seconds immediately following death. Perfusion fluid consisted of physiologic saline, pH = 7.4, 37°C (33), containing 6% dextran (blank) or 2.7% albumin plus 0.6 mg/mL of indocyanine green to mark blood vessels. The efficacy of the vascular washout procedure was verified as greater than 90% in separate experiments (Supplementary Fig. 2). Samples were also collected from other tissues, as well as blood and serum, for comparative analysis. Frozen sections were cut at 20 μm with a cryostat (−23°C) and mounted on glass slides.

Drug efficacy studies were carried out with mice treated intravenously with clinical grade paclitaxel (6 mg/kg) or doxorubicin (5 mg/kg) once a week for 4 weeks and the number of metastatic lesion was tabulated as previously described (49, 50).

Fluorescence analysis of BTB permeability, tumor distribution, and vascular density

Fluorescence analyses were performed using an Olympus MVX10 microscope with a 2× objective (NA = 0.5) and an optical zoom of (0.63–6.3)×. Excitation and emission filters were 470 ± 40 and 525 ± 50 nm for eGFP, 560 ± 55 and 645 ± 75 nm for Texas Red dextran, and 740 ± 35 nm and 780 longpass filter for near-infrared indocyanine green. Exposure time varied from 300 to 500 milliseconds for initial scans of whole tissue sections to 15 milliseconds for quantitative analysis of tumor regions. For Texas Red dextran, total fluorescence intensity in a region of interest was converted to sum voxel intensity per gram of tissue. Volume was calculated as area (cm^2) × 0.002-cm thickness corrected for density of 1.04 g/cm^3. To convert fluorescence intensity to concentration, standard curves were generated (Supplementary Fig. 3), similar to autoradiography (46). Brain (500 mg) was excised and homogenized to uniformity with 100 μL of saline containing different concentrations of Texas Red dextran. The final mixture was flash frozen in isopentane and sliced into 20-μm sections. Similarly, blood samples were spiked with concentrations of dye, 1 μL of samples were placed on glass slides and dried, and then total fluorescence intensity for the blood drop was measured. Texas Red dextran fluorescence intensity did not differ between standards prepared from brain or tumor, or from solutions of differing pH (6.0–7.6) or Na^+/Ca^{2+} concentration (data not shown). Texas Red dextran sum intensity was stable within ±5% with repeat fluorescent exposures (15–1,500 milliseconds). Fluorescent image analysis was performed using Slidebook 5.0 program (Olympus). Vascular density and surface area were calculated using binary masks in which vessels were defined by indocyanine green fluorescence of 3-fold or greater above background.

Radioactive analysis and phosphorescence imaging

^{14}C radioactivity (dpm) in tissues and fluids was determined by liquid scintillation counting, corrected for quench and background. Radiotracer imaging was carried out by exposure of tissue sections to phosphor screens in cassettes for 2 to 14 days, followed by data analysis using a Fuji phosphoimager with tissue-calibrated ^{14}C standards (GE Healthcare). Phosphor images were converted to color-coded ^{14}C tissue concentrations, using MCID software (Imaging Research). Typical brain ^{14}C concentrations varied from 40 to 80 nCi/g for ^{14}C-AIB and 0.5 to 3 nCi/g for ^{14}C-paclitaxel and ^{14}C-doxorubicin. Limits of detection and quantitation for ^{14}C equaled 0.1 and 0.3 nCi/g, respectively (Supplementary Fig. S3). *In vivo* drug integrity was confirmed for paclitaxel and doxorubicin using high-performance liquid chromatography (HPLC) and liquid chromatography/tandem mass spectrometry (Varian; refs. 51, 52).

Kinetic analysis

Barrier passive permeability was determined by measuring the unidirectional blood-to-brain– or –metastasis transfer coefficient (K_{in}). Briefly, K_{in} was determined for ^{14}C-AIB and 3-kDa Texas Red uptake into normal brain in control animals, using the multiple time uptake approach [circulation time = 5–30 minutes (45, 46)]. BBB K_{in} was found to be $2.9 \pm 1.1 \times 10^{-5}$ and $1.1 \pm 0.4 \times 10^{-5}$ mL/s/g, respectively (n = 8–10). It was converted to vascular permeability-surface area product (PS) using the following equation:

$$PS = -F \ln\left(1 - \frac{K_{in}}{F}\right) \quad (A)$$

where F is the cerebral blood flow (45, 53). Cerebral blood flow was measured using ^{14}C-nicotine (54) and was reduced 30% to 70% in most brain metastases (data not shown). BTB K_{in} was taken as equivalent to PS, as even with the highest BTB K_{in} values in brain metastases (i.e., 35-fold elevation for ^{14}C-AIB), K_{in} differed from PS by less than 10%. Once normal, BBB PS was established for control animals, single-time uptake (10 minutes) was used to measure PS in most animals (46). Individual metastasis PS and drug concentrations were considered elevated when they exceeded mean ± 3SD of matching normal brain. For simplicity in this article, PS is referred to as permeability.

Cresyl violet staining

Sections were fixed in 4% paraformaldehyde (PFA) in PBS for 10 minutes, rinsed and immersed in 0.1% cresyl violet

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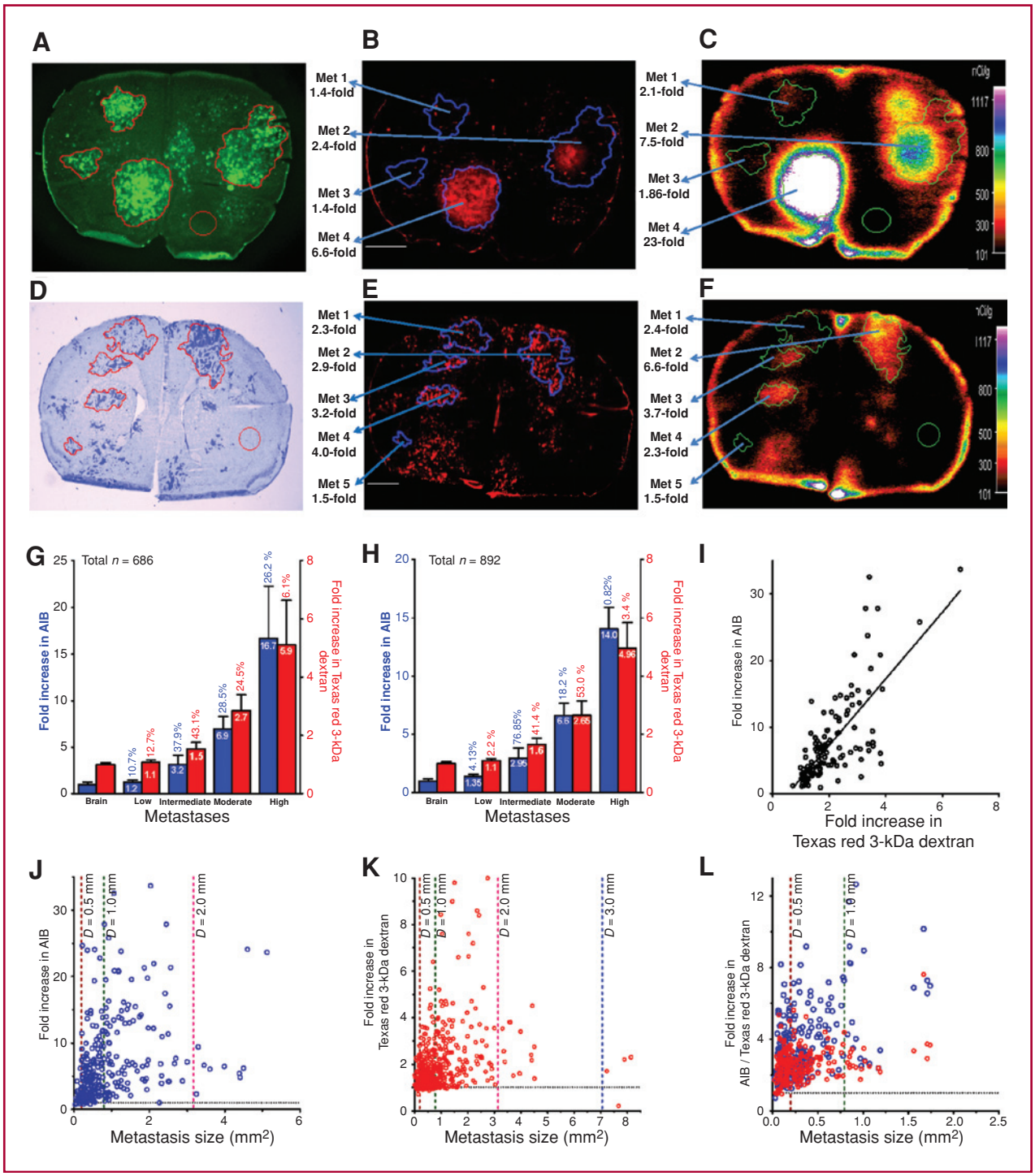

Fig. 1. Experimental brain metastases of breast cancer exhibit heterogeneous passive permeability with weak correlation to lesion size. A and D, representative images of metastases of A, eGFP-transfected 231-BR-Her2, or D, 4T1-BR5 cells (cresyl violet staining), respectively. B, C, E, and F, images of the same brain section showing metastases and brain accumulation of 3-kDa Texas Red dextran and ^{14}C-AIB with vascular washout. White scale bar represents 1 mm. The fold increase (mean ± SD) in ^{14}C-AIB (blue bars) and 3-kDa Texas Red dextran (red bars) PS is shown between brain and 231-BR-Her2 brain metastases (G) and 4T1-BR5 brain metastases (H). Metastases were separated into 4 groups on the basis of the magnitude of the permeability change compared with mean brain. Values represent the percentage of metastases in each group and the mean fold increase of tracer in each group. I, fold increase ^{14}C-AIB (over normal brain) plotted versus fold increase 3-kDa Texas Red dextran in 231-BR-Her2 metastases ($r^2 = 0.54$, $P < 0.0001$; $n = 127$). J and K, fold elevation of ^{14}C-AIB (blue dots; $n = 288$) and 3-kDa Texas Red dextran (red dots; $n = 535$) in individual 231-BR-Her2 brain metastases compared with brain distant from tumor graphed versus metastasis size (mm^2). Brain distant from tumor equals 1.0 and is represented by the horizontal line. Diameter in 1 plane is shown in vertical lines. L, fold elevation of metastasis ^{14}C-AIB (blue dots) and 3-kDa Texas Red dextran (red dots) versus metastasis size in 4T1-BR5 ($n = 229$).

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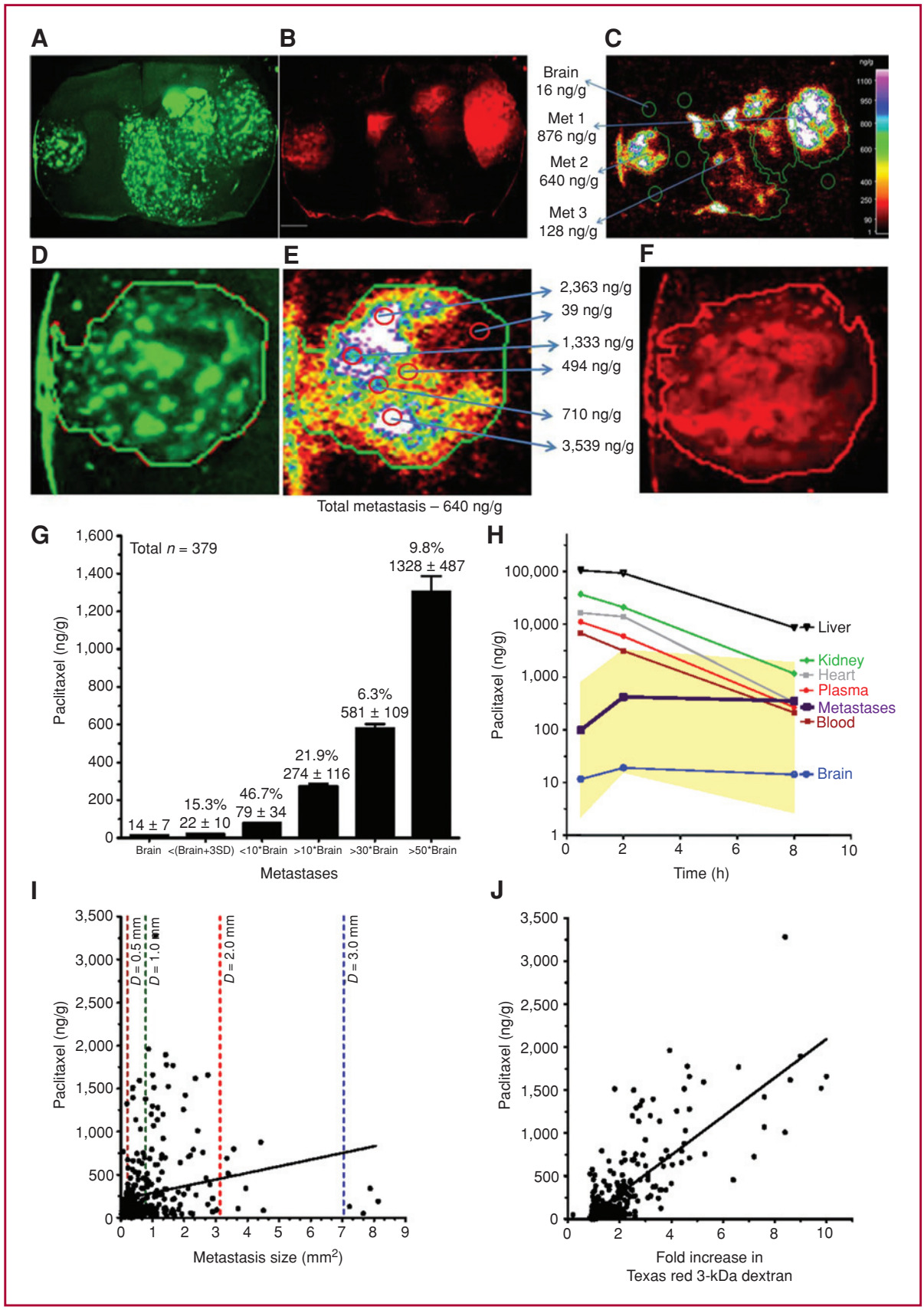

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acetate (15 minutes), and rinsed again. Sections were processed for differentiation, dehydration, and clearing in 70% ethanol (15 seconds), 95% ethanol (30 seconds), and 100% ethanol (30 seconds), respectively. Brightfield images were captured with a 2× objective and superimposed on fluorescent images to colocalize drug or tracer permeability.

Immunofluorescence

Tissues were rehydrated in PBS and then fixed in cold acetone for collagen type IV (Millipore) and desmin antibody (Dako), ice-cold methanol for ABCB1 (Santa Cruz Biotechnology), or cold 4% PFA for cleaved caspase-3 (Cell Signaling) and cytokeratin (AbCam). After 3 PBS washings (5 minutes), they were blocked with either 4% or 10% goat serum or 0.2% Triton-X 100 (1 hour). Primary antibodies were added, followed by overnight incubation at 4°C. CD31 antibody (BD Pharmingen) was coincubated with each of the previous antibodies. After washing, secondary antibodies and/or 4′,6-diamidino-2-phenylindole (DAPI; 1 mg/mL) were added (1 hour). Slides were washed, Dako mounting medium was added, and cover slips were applied. For each metastasis within a section identified as permeable or nonpermeable, $CD31^+$ blood vessels were manually identified and the surface area (μm^2) of the vessel was calculated along with the signal intensity of desmin, collagen type IV or ABCB1 per vessel. For each metastasis, the results are shown as a ratio of the mean antibody intensity per total vessel area.

Statistical analysis

Prism 5 software was used to analyze the data. Results are presented as mean ± SD. Statistical differences were assessed using nonparametric Mann–Whitney or Kruskal–Wallis tests. Pearson's correlation was used to calculate r^2. All tests were 2 sided with $P < 0.05$ for statistical significance. The D'Agostino–Pearson omnibus K2 normality test was used to determine whether data conformed to the normal distribution. Statistical values obtained with this test for normal brain were $P = 0.232$ for ^{14}C-paclitaxel ($n = 257$), $P = 0.220$ for ^{14}C-doxorubicin ($n = 118$), and $P = 0.143$ for AIB PS ($n = 133$).

Results

BTB permeability

BTB integrity was assessed from measured PS changes using two markers, 103-Da ^{14}C-AIB and 3-kDa Texas Red dextran, which bracket the molecular weight range of most nonbiological chemotherapeutic drugs (Fig. 1). For both models, metastatic lesions were operationally defined as cancer cell clusters within 100 μm of each other, based on the diffusion limit of oxygen. Using this definition, metastases ranging in size from ~300 μm to ~3 mm in diameter were observed with both the 231-BR-Her2 (Fig. 1A) and 4T1-BR5 models (Fig. 1D). Representative examples of brain sections containing multiple metastases with heterogeneous permeability are illustrated in Figure 1B, C, E, and F. The cumulative data for 231-BR-Her2 ($n = 686$) and 4T1-BR5 ($n = 892$) brain metastases show that a) greater than 89% of brain metastases exhibited statistically increased BTB permeability compared with normal brain to one or both markers, b) changes in permeability were intermediate (1.5- to 3.2-fold) in most cases (37%–76% of metastases), and c) in only a subset (0.8%–26% of metastases) were there prominent permeability changes, defined as greater than 10-fold for AIB and greater than 5-fold for 3-kDa Texas Red dextran (Fig. 1G and H). Changes in permeability were noted for both markers across the range of metastases from small micrometastases (<1-mm diameter) to large, clinically detectable lesions (>1-mm diameter). A significant correlation of permeability ($r^2 = 0.54$) was observed for the two permeability markers when measured in the same lesions (Fig. 1I). However, no clear relationship was observed between permeability and lesion size, with r^2 ranged from 0.09 to 0.23 for both markers in both models (Fig. 1J–L), or morphology (e.g., compact vs. diffuse; Supplementary Figs. 4 and 5). Comparable results were found in metastases without vascular washout (Supplementary Fig. 6). The results show that most brain metastases exhibit increased BTB passive permeability compared with normal brain, with marked heterogeneity in both small and larger metastases.

Brain metastasis distribution of paclitaxel

Next, we asked the question whether and to what extent variable BTB permeability alterations translated into differential uptake of two commonly used breast cancer chemotherapeutic agents, paclitaxel and doxorubicin, at pharmacologic doses. Representative images for 231-BR-Her2 metastases are shown in Fig. 2A–F. Paralleling what was found in BTB passive permeability, ^{14}C-paclitaxel concentrations were heterogeneous both between (Fig. 2A–C) and within (Fig. 2D–F) metastases, with some

Fig. 2. Variable paclitaxel uptake in 231-BR-Her2 brain metastases that correlates with 3-kDa Texas Red dextran accumulation. ^{14}C-Paclitaxel distribution in 231-BR-Her2 metastases after intravenous administration of 10 mg/kg of paclitaxel (Taxol formulation). Distribution of eGFP (A), 3-kDa Texas Red dextran [10-minute circulation (B)], and ^{14}C-paclitaxel [8 hours (C)], followed by a 30-second vascular washout. White scale bar represents 1 mm. Heterogeneous distribution is shown within one representative brain metastasis (D, eGFP; E, ^{14}C-paclitaxel; and F, 3-kDa Texas Red dextran). G, ^{14}C-paclitaxel concentration (ng/g) in brain and 231-BR-Her2 brain metastases. Values represent the percentage of all metastases in each group, and the mean ± SD of ^{14}C-paclitaxel concentration in each group. H, mean brain metastasis drug concentration was measured at different times (30 minutes–8 hours) and related to that in brain distant from tumor, plasma, blood, and peripheral tissues ($n = 3$ animals per point). Yellow areas show highest and lowest concentrations observed in brain metastases at the 3 time points. Calculated area under the curve cumulative exposure (in μg h/g) equaled 0.18 in brain, 2.9 in average brain metastasis, and 80 to 400 in peripheral tissues. I, graphs of 231-BR-Her2 for ^{14}C-paclitaxel concentration versus lesion size of individual metastasis. Correlation was minimal between brain metastasis paclitaxel concentration and lesion size (Pearson $r^2 = 0.037$). Dashed lines represent diameter. J, correlation of ^{14}C-paclitaxel concentration versus fold increase of 3-kDa Texas Red dextran permeability of individual metastases. An appreciable correlation of paclitaxel concentration to 3-kDa Texas Red dextran was noted (Pearson $r^2 = 0.605$, $P < 0.0001$; $n = 354$).

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lesions increasing by greater than 200-fold. In a cumulative analysis involving 231-BR-Her2 ($n = 379$) brain metastases, ^{14}C-paclitaxel concentrations were elevated in 85% of lesions, with the majority (47%) increasing by less than 10-fold and only a small subset (10%) increasing by greater than 50-fold (Fig. 2G). Average brain metastasis ^{14}C-paclitaxel concentration exceeded normal brain by 10- to 20-fold at all time points from 30 minutes to 8 hours ($P < 0.05$; Fig. 2H) but was an order of magnitude less than that of peripheral tissues, such as liver or kidney ($P < 0.05$). Radiochemical integrity was confirmed as greater than 95% in serum and brain at 30 minutes and 2 hours and greater than 80% at 8 hours. No clear correlation was found between metastasis ^{14}C-paclitaxel concentration and lesion size (Fig. 2I) or morphology (Supplementary Fig. 7), whereas an appreciable correlation ($r^2 = 0.59$) was noted with BTB passive permeability to 3-kDa Texas Red (Fig. 2J). Similar trends were observed for ^{14}C-paclitaxel distribution in 4T1-BR5 brain metastases (Fig. 3A–E). In a number of 4T1-BR5-injected animals, metastases were found in peripheral tissues (e.g., liver, kidney, lung) with ^{14}C-paclitaxel concentrations (6,000–30,000 ng/g; Fig. 3F–H), notably higher than brain metastasis concentrations in the same animals (150–2,000 ng/g). The data are consistent with the hypothesis that BTB function, though partially compromised, is still present and limits drug delivery to a significant extent relative to that found in non-CNS metastases or peripheral tissues.

Paclitaxel rarely induced apoptosis in brain metastatic tumor cells and did not show significant efficacy

To determine whether paclitaxel achieved cytotoxic concentrations in brain metastases, 231-BR-Her2 brain sections from animals exposed to paclitaxel for 8 hours were stained for cleaved caspase-3 as a marker of apoptosis (55, 56). As shown in a representative experiment (Fig. 4A–C), multiple tumor cells exhibiting enhanced cleaved caspase-3 staining were found in brain metastases with ^{14}C-paclitaxel concentrations greater than 1,000 ng/g, whereas little or no staining was found in 231-BR-Her2 metastases with low ^{14}C-paclitaxel concentration (<200 ng/g; Fig. 4D–F). Similar data were observed in the 4T1-BR5 brain metastasis model (Supplementary Fig. 8). The results show that paclitaxel-induced cytotoxic effects are observed in only a small subset (~10%) of brain metastasis regions that have markedly elevated paclitaxel concentrations (>1,000 ng/g).

The ability of paclitaxel to reduce the number and size of 231-BR-Her2 metastatic lesions in the brain was tested. Weekly treatment of 6 mg/kg of paclitaxel was administered beginning 3 days postinjection of tumor cells for 4 weeks. At necropsy, brains were dissected sagittally and 10 sections, 1 every 300 μm, from 1 hemisphere were H&E stained. The number of micro- and large metastases was tabulated as previously described (49, 50). Paclitaxel-treated mice had a mean of 175 (95% confidence interval: 103–247) micrometastases and 6.9 (2.9–10.8) large metastases per section compared with vehicle control–treated mice with 128 (99–175) and 6.9 (4.9–9), respectively. Thus, the low degree of apoptosis observed agreed with ineffective chemotherapeutic ability despite the fact that the 231-BR-Her2 cell line is sensitive to paclitaxel *in vitro* with an IC_{50} of 4 to 6 nmol/L (data not shown).

Brain metastasis distribution of doxorubicin

To determine whether other chemotherapeutic drugs behaved similarly to paclitaxel, matching experiments were conducted with ^{14}C-doxorubicin (6 mg/kg, i.v.) in the 231-BR-Her2 (Fig. 5A–C) and 4T1-BR5 (Fig. 5D–F) models. ^{14}C-Doxorubicin uptake varied widely among brain metastases in both models and, like paclitaxel, correlated significantly with BTB passive permeability increases to 3-kDa Texas Red dextran (Fig. 5H). The range of observed ^{14}C-doxorubicin concentrations varied from 30 to greater than 1,300 ng/g among brain metastases (Fig. 5G–I), with similar findings for both drugs in animals that were not subjected to vascular washout (Supplementary Fig. S9). ^{14}C-Doxorubicin integrity was confirmed by HPLC to be greater than 95%. Similarly, doxorubicin was not efficacious in inhibiting the number or size of 231-BR-Her2 metastatic lesions in the brain. Doxorubicin administered at a 5-mg/kg dose once a week for 4 weeks yielded a mean of 144 (109–179) micrometastases and 5.2 (3.4–7.0) large metastases per section compared to vehicle control–treated mice with 128 (99–175) and 6.9 (4.9–9.0), respectively. The results support the conclusion that variable drug distribution is generalizable across both the models. Most experimental brain metastases attained low drug concentrations (<200 ng/g), which were not efficacious *in vivo*.

Correlation between BTB permeability and vascular remodeling

The causes of BTB heterogeneity within metastases of the same brain are unknown. The role of angiogenesis in brain metastasis formation is debated, with several reports showing co-option of existing vasculature by intravasated tumor cells (57, 58), whereas other reports support a role of vascular endothelial growth factor–induced angiogenesis (59). Therefore, we tested whether vascular density, as a standard measure of angiogenesis, was greater in BTB permeable versus nonpermeable metastases. Representative brain sections from animals injected with indocyanine green as a vascular marker are shown in Figure 6A–C. The combination of 3-kDa Texas Red dextran and indocyanine green allowed simultaneous quantitative imaging of BTB PS and vascularity, respectively, in individual metastases, as shown in representative images for one permeable (Fig. 6G–J) and one nonpermeable lesion (Fig. 6K–N). No increase was observed in vascular density for permeable lesions in either model (Fig. 6D). Furthermore, no increase was noted when groups were plotted versus metastasis size (Fig. 6E and F).

If the extent of angiogenesis does not explain the variable BTB integrity of experimental brain metastases, vascular remodeling or normalization could be contributory (60). Therefore, expression levels were determined by staining

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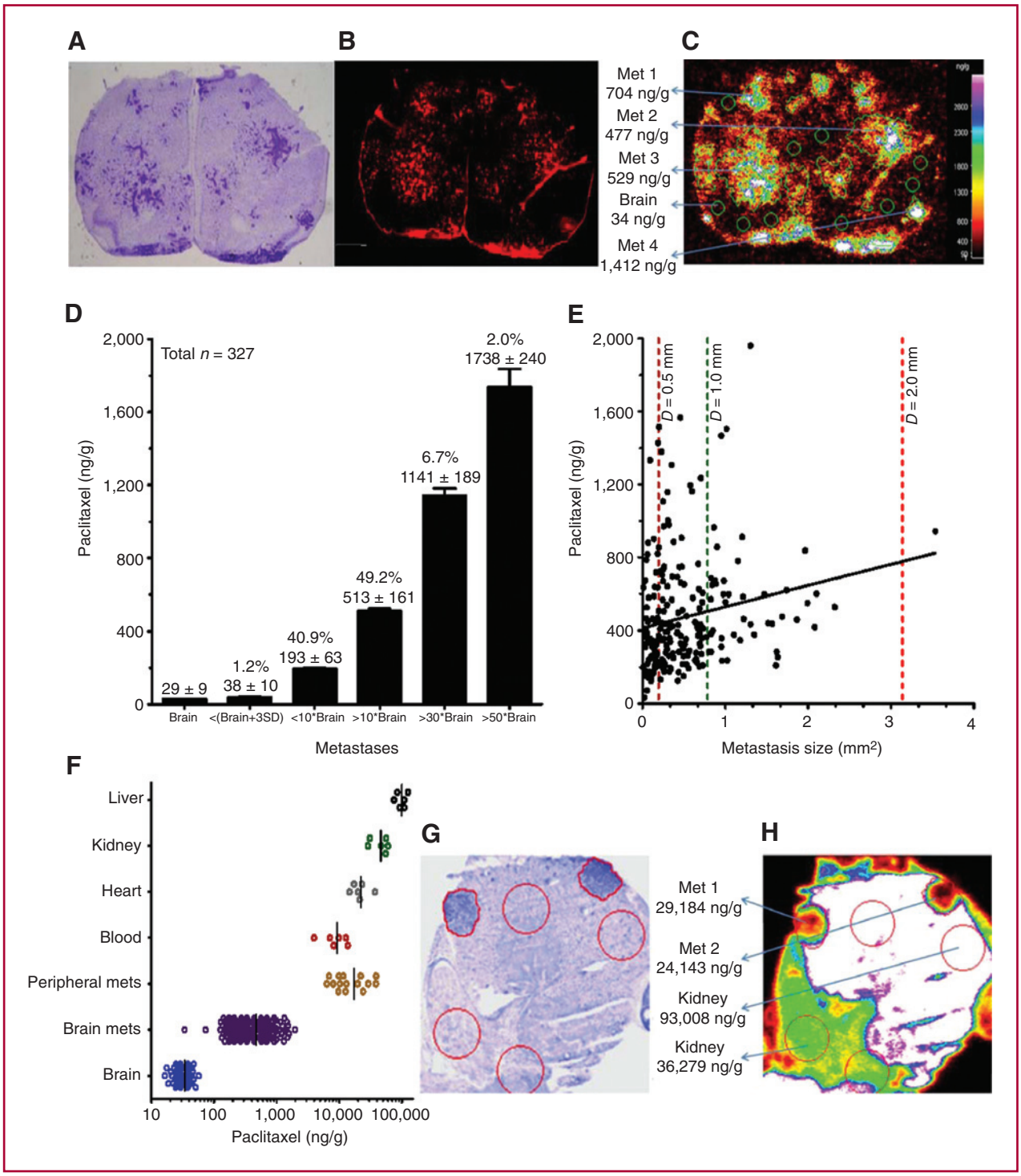

Fig. 3. Variable paclitaxel uptake in 4T1-BR5 brain metastases of breast cancer. A–C, ^{14}C-paclitaxel distribution in representative 4T1-BR5 brain metastases. 3-kDa Texas Red permeability marker circulated for 10 minutes, whereas 10 mg/kg of ^{14}C-paclitaxel circulated for 30 minutes (after circulation of both tracers, there was a 30-second vascular washout). A, brightfield image of cresyl violet–stained lesions. B, 3-kDa Texas Red dextran uptake (white scale bar represents 1 mm). C, ^{14}C-paclitaxel concentration. D, ^{14}C-paclitaxel concentration (ng/g) in brain and 4T1-BR5 brain metastases. E, ^{14}C-paclitaxel concentration versus lesion size of individual metastases. Correlation was minimal between brain metastasis paclitaxel concentration and lesion size (Pearson $r^2 = 0.034$). Dashed lines represent diameter. F, ^{14}C-paclitaxel distribution (30 minutes) in 4T1-BR5 metastases in brain and peripheral tissues, as well as in matching surrounding normal tissues. The distribution of individual data points for brain and peripheral tissues is shown as well as the mean; $n = 3$ mice. G, representative section showing cresyl violet–stained 4T1-BR5 kidney metastases. H, ^{14}C-paclitaxel concentration in kidney section.

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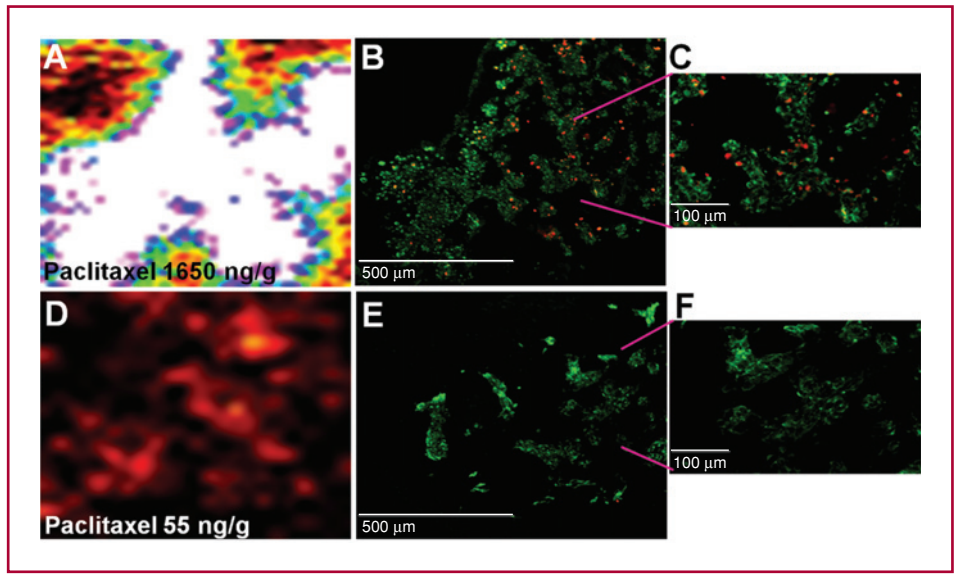

Fig. 4. Positive cleaved caspase-3 staining in brain metastases with high paclitaxel accumulation. Representative images of (A) high (representing <10% of lesions) and (D) low ^{14}C-paclitaxel uptake in 231-BR-Her2 experimental metastases. Presence of cleaved caspase-3 staining (red) was found in human cytokeratin-positive tumor cells (green) within brain metastases with markedly elevated paclitaxel concentration (B and C) but not in metastases with low paclitaxel concentration (E and F); $n = 3$–5 animals per group.

for three BTB components: pericyte desmin protein, basement membrane collagen type IV, and endothelial ABCB1 P-glycoprotein efflux transporter in permeable and nonpermeable 231-BR-Her2 brain metastases. Briefly, brain sections were evaluated for 3-kDa Texas Red dextran immunofluorescence to identify permeable and nonpermeable metastases. On the adjacent brain section, the relative expression level of each BTB component was determined by coimmunoflourescence in every visible capillary within a metastasis and normalized to CD31 capillary area by using an automated imaging system. When the mean expression levels of 15 permeable and 20 nonpermeable metastases were compared, an association was observed for high desmin expression in permeable metastases ($P = 0.0005$; Fig. 7A and B). When similar staining was performed for basement membrane collagen type IV, a trend toward lower collagen expression was observed in permeable lesions (Fig. 7C and D). This pattern is opposite to that for desmin and is consistent with specific BTB remodeling. No clear relationship was observed between ABCB1 P-glycoprotein efflux transporter expression level and metastasis passive permeability (Fig. 7E). The association of enhanced pericyte desmin protein with elevated permeability may suggest a role of vascular remodeling in BTB compromise.

Discussion

This study, through a combination of sensitive fluorescence and phosphorescence imaging methods, provides quantitative insights into the relationships between BTB integrity, drug delivery, and drug action in two models of brain metastases of breast cancer. The results show clearly for the first time that while the BTB is impaired in most brain metastases, residual BTB function generally limits the distribution of paclitaxel and doxorubicin to subtherapeutic levels. For paclitaxel, cytotoxic concentrations (i.e., cleaved caspase-3 staining) were reached only in a subset (<10%) of the leakiest brain metastases in which drug concentration exceeds 1,000 ng/g. In contrast, drug concentrations in systemic metastases (outside the CNS) exceeded those in brain lesions by greater than 10-fold and many tissues outside the brain had drug concentrations ranging from 10,000 to 100,000 ng/g. In agreement with these data, treatment with paclitaxel or doxorubicin did not reduce metastatic burden in the brain when the drugs were administered over a 4-week time course of assay. The results highlight the impact of the BBB and BTB to compromise therapeutic efficacy of poorly penetrating chemotherapeutic agents in brain metastases of breast cancer.

This study also provides valuable new methodology for combined quantitative analysis of barrier integrity and drug distribution in experimental animal models. Although fluorescent indicators of BBB integrity have been reported previously, these methods have generally been qualitative and have not allowed analysis of marker distribution in small regions (<1 mm^3) of brain tissue. Herein, we provide a coupled quantitative fluorescence and autoradiographic method that has been adapted from prior elegant double or triple autoradiographic techniques (61, 62). This current methodology allows the quantitative measurement of changes in passive permeability and vascularity using two or more fluorescent probes and can provide data within a few hours with less than 1-μm

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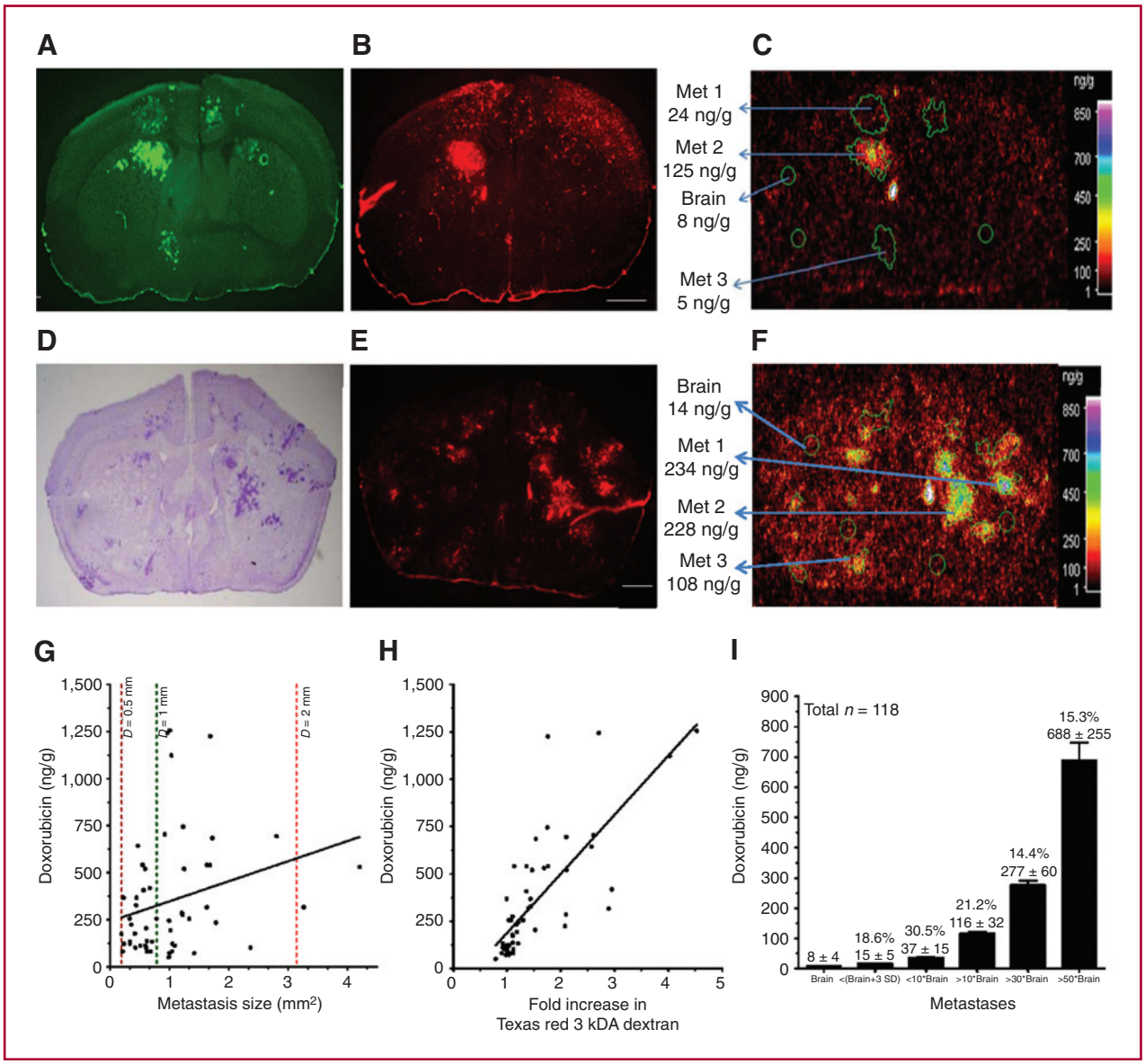

Fig. 5. Heterogeneous doxorubicin uptake in 231-BR-Her2 brain metastases of breast cancer: ^{14}C-doxorubicin distribution in representative images for 231-BR-Her2 (A–C) and 4T1-BR5 (D and F) brain metastases. 3-kDa Texas Red permeability marker circulated for 10 minutes, whereas 6 mg/kg of ^{14}C-doxorubicin circulated for 30 minutes, followed by a 30-second vascular washout. A, eGFP imaging. D, cresyl violet staining. B and E, 3-kDa Texas Red dextran uptake. C and F, ^{14}C-doxorubicin uptake. G, ^{14}C-doxorubicin concentration versus lesion size of individual metastases. Correlation was minimal between brain metastasis doxorubicin concentration and lesion size (Pearson $r^2 = 0.070$). Dashed lines represent diameter. H, ^{14}C-doxorubicin correlated appreciably with fold increase in 3-kDa Texas Red dextran permeability (Pearson $r^2 = 0.591$, $P < 0.0001$; $n = 54$). Serum ^{14}C-doxorubicin was shown to be greater than 95% intact at 30 minutes of circulation, using HPLC. I, ^{14}C-doxorubicin concentration (ng/g) in brain and 231-BR-Her2 brain metastases. Metastases were separated into 5 groups on the basis of the magnitude of the ^{14}C-doxorubicin concentration relative to normal brain. Values represent the percentage of all metastases in each group, and the mean ± SD of ^{14}C-doxorubicin concentration in each group.

resolution, as compared with days to weeks with 10- to 25-μm resolution using traditional autoradiography (63). Furthermore, with ^{14}C phosphorescence, drug distribution can be mapped in 10-μm pixels at levels (~0.3 nCi/g) significantly below most other methods, including standard film autoradiography (~10 nCi/g). For example, within this study, brain paclitaxel measurements at the limit of quantitation for ^{14}C correspond to concentrations of ~5 ng/g of tissue, which in a small metastasis (i.e., 100 × 100 × 20 μm) represents femtogram quantity of drug. Overall, the method allows us the ability to dissect the roles of BTB integrity, vascular drug delivery, and chemotherapeutic action in the same tissue slice.

A striking finding of this report is the marked heterogeneity of BTB integrity and drug distribution among metastases. On the basis of analysis of greater than

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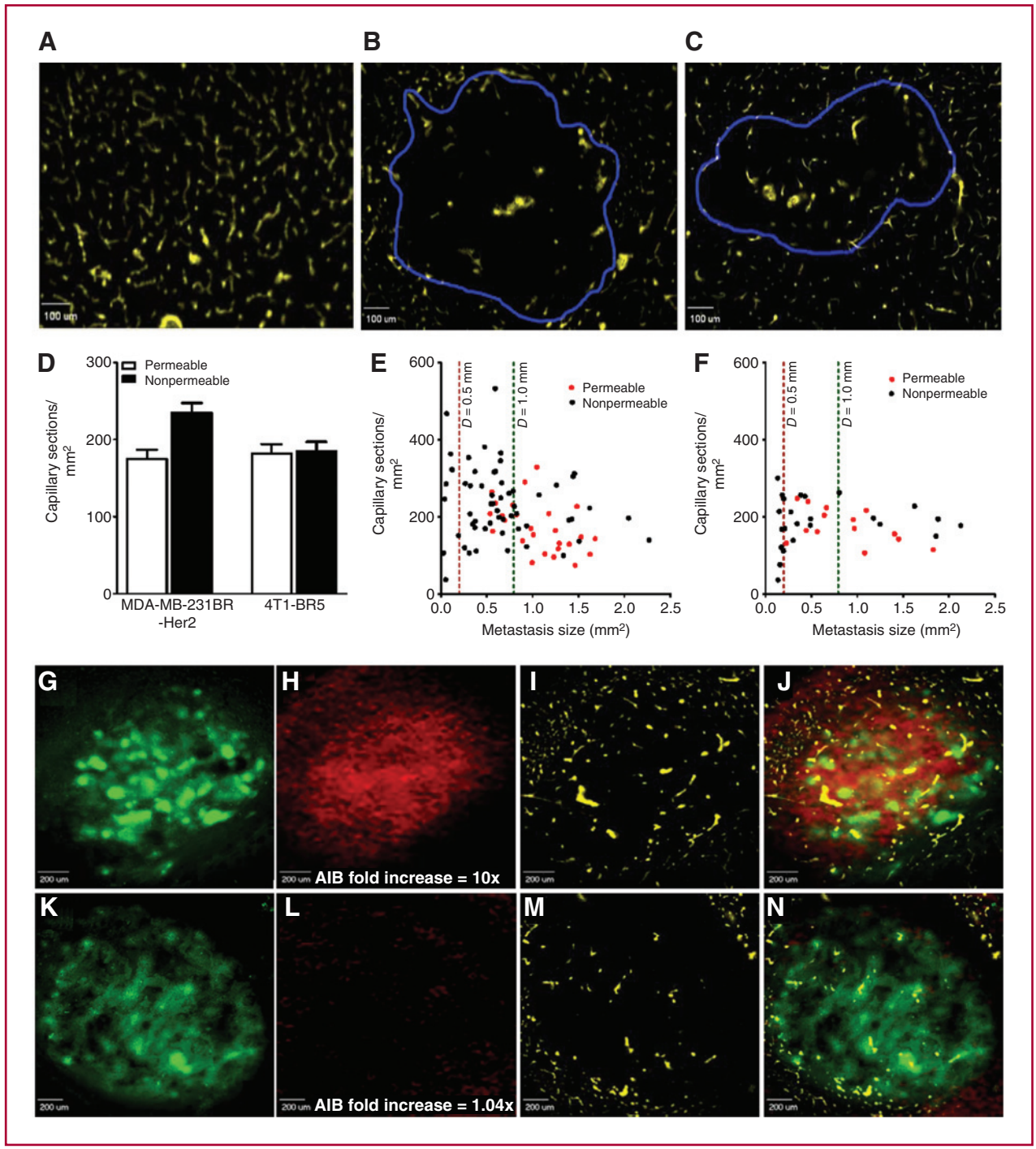

Fig. 6. Vascular density is reduced and does not correlate with BTB permeability in two experimental models of brain metastasis of breast cancer: Representative images of the vascular density of (A) normal brain, (B) 231-BR-Her2, and (C) 4T1-BR5 metastases (capillaries, yellow; metastasis boundary, blue). D, calculated vascular densities of both permeable and nonpermeable metastases. E and F, vascular density and metastasis size for permeable and nonpermeable tumors. E, 231-BR-Her2. F, 4T1-BR5. Data were obtained by injection and circulation of ^{14}C-AIB (10 minutes) and indocyanine green (1 minute) bound to albumin as the vascular tracer. Elevated BTB permeability was not associated with increased vascular density by analysis of linear regression slopes or intercepts ($P > 0.05$). Representative images showing simultaneous multichannel quantitative imaging of eGFP (G and K), ^{14}C-AIB by phosphorescent imaging (H and L), vascular density by near-infrared imaging of indocyanine green (I and M) of a permeable (G–J) and nonpermeable lesion (K–N); J and N are combined multichannel images.

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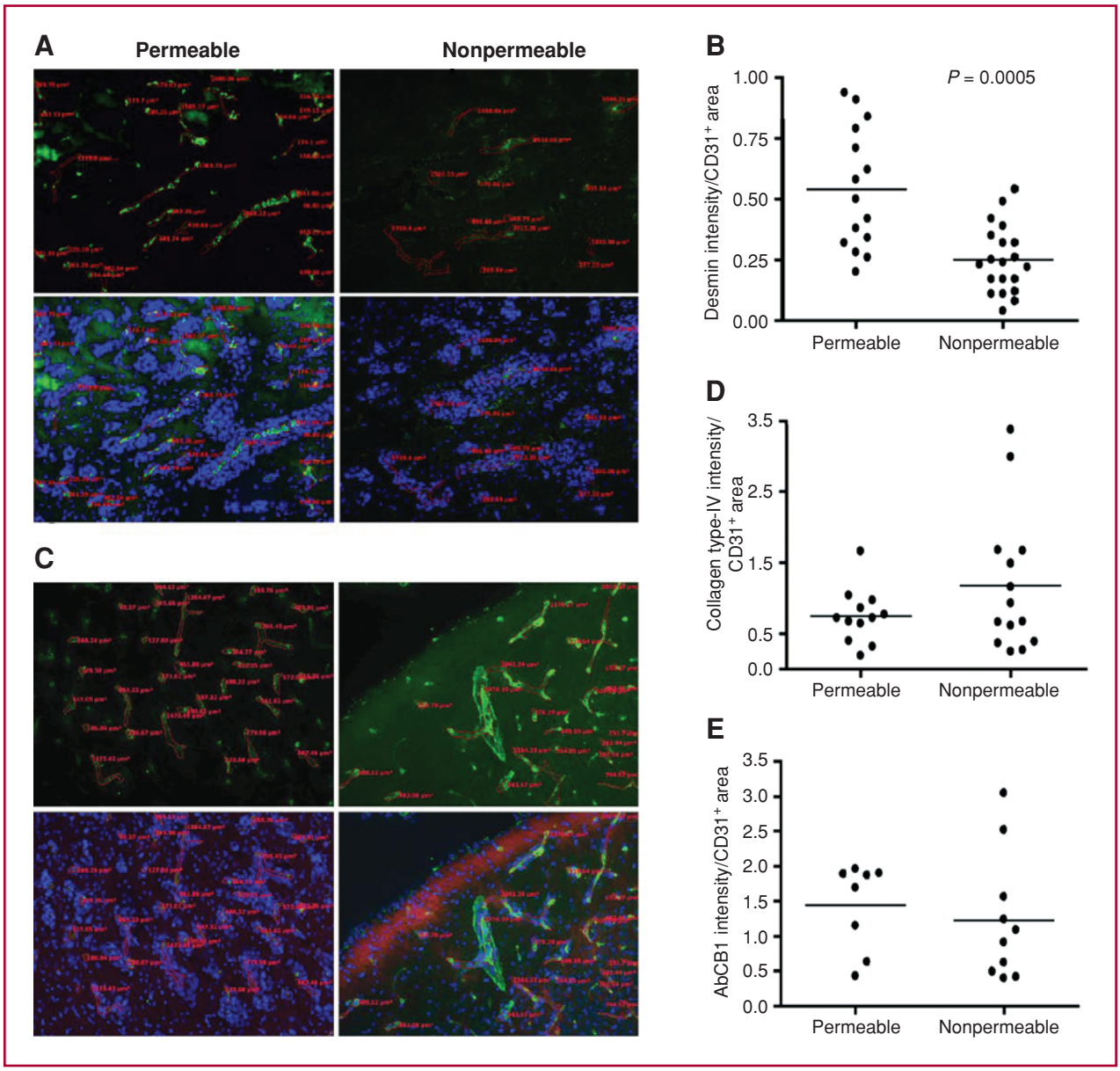

Fig. 7. Passive permeability of experimental brain metastases is associated with BTB remodeling. A, BTB permeability is associated with desmin overexpression by immunofluorescent staining. Representative images of desmin staining in adjacent permeable and nonpermeable metastases from the same brain. CD31 (capillaries, red), desmin (green), and DAPI (nuclei, blue). B, desmin expression per $CD31^+$ area plotted for 35 permeable and nonpermeable metastases. Mean values are indicated as lines. Expression intensity was ~2-fold elevated in permeable versus nonpermeable metastases ($P = 0.0005$, Mann–Whitney test). C, representative section stained for type IV collagen (green). Other colors same as A. D and E, plotted data for type IV collagen and ABCB1 ($P > 0.05$).

2,000 metastases, statistically significant changes in BTB permeability were observed in ~89% of 231-BR-Her2 and ~96% of 4T1-BR5 brain metastases. This is consistent with the 231-BR model showing Gd-DPTA enhancement by MRI *in vivo* (43) and with limited prior observations of BTB integrity in experimental models of brain metastases of breast cancer (64, 65). The data, herein, show that the BTB is variably compromised in most brain metastases greater than a minimal size (>0.1–0.2 mm^2), whereas historically, significant integrity changes were primarily associated with large lesions (>1–4-mm diameter), in which diffusion distances compromise oxygen and nutrient delivery and lead to angiogenesis (66). With tumor cell delivery via the vasculature, two patterns of tumor growth, compact/solid and diffuse/infiltrative, have been noted for brain metastases (64, 65). Diffuse/infiltrative lesions may arise, in part, through perivascular tumor spread via blood vessel co-option (67, 68). In our data, no

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clear relation was found between changes in the integrity of the BTB and metastasis size or diffuse versus compact structure. A number of small or diffuse lesions were found with marked BTB compromise (>10-fold increase for AIB), whereas some large, compact tumors were observed with only limited elevations. The cause of this heterogeneity warrants further study.

Although the BTB had observable permeability changes in most brain metastases, this should not be taken as evidence of the absence of barrier function. For brain metastases from both models, the average permeability of ^{14}C-AIB (~3-fold greater than normal brain) was only 2% to 5% of that of peripheral breast tumor (69) or circumventricular regions of the brain without a BBB (70). Even in the leakiest of brain metastases (~33-fold increase), permeability was still less than 12% of that in a peripheral breast tumor (70). Similarly, average paclitaxel concentration in brain metastases was on average only 3% of levels in metastases in other tissues; even in the highest cases, concentrations did not exceed 15% of that in peripheral metastases (Fig. 3F). Thus, BTB function in these models may be viewed as only partly compromised, retaining a significant ability to impede chemotherapeutic uptake.

The data also provide clear correlations between drug concentration and chemotherapeutic effect. Paclitaxel-induced apoptosis was noted only in brain metastases in which drug concentrations exceeded 1,000 ng/g (>1.2 μmol/L) for both the 231-BR-Her2 and 4T1-BR5 models. Correction of this value for reported paclitaxel tissue binding [free fraction = 0.0028; (71)] suggests that apoptosis was noted only at free paclitaxel concentrations of 1.2 μmol/L × 0.0028 ≥ 3.4 nmol/L. This value agrees well with the *in vitro* paclitaxel IC_{50} of 3 nmol/L for the 231 parent cell line (72) and ~4 to 6 nmol/L with the 231-BR-Her2 model. In contrast, doxorubicin, which attains similar maximum concentrations in brain metastases but is greater than 20 times less potent [IC_{50} > 100 nmol/L (73); data not shown] may not produce significant cytotoxicty in brain metastases *in vivo*. Consistent with this finding, we have not detected elevated cleaved caspase-3 staining in brain metastases from animals treated with doxorubicin. Average paclitaxel concentrations of 2,507 and 1,614 ng/g were reported by Fine and colleagues (29) in the center and periphery of human brain metastases removed by surgery. Because these values are in the same range as reported in this study, our data are consistent with limited efficacy of paclitaxel against human brain metastases (10, 12).

The combined imaging methods used in this article highlight the potential role of vascular remodeling in BTB compromise. An unexpected relationship was observed between increased desmin staining, a pericyte protein, and elevated BTB permeability. Other aspects of BTB architecture, including staining for basement membrane type IV collagen and efflux pump ABCB1, did not exhibit this trend. Most studies have observed a positive relationship between pericyte coverage and maintenance of BBB integrity and function, including upregulation of P-glycoprotein expression (reviewed in ref. 74). However, several reports are consistent with our observations. For example, pericyte abundance or remodeling has been associated with increased BBB permeability in *in vitro* models of hypoxia and sepsis (75, 76) and *in vitro* co-cultures of brain vascular cells (77, 78). In one study, pericytes collaborated with astrocytes to maintain BBB integrity under low levels of hypoxia but, during acute hypoxia, pericytes exacerbated BBB disruption (75). In another situation, the inflammatory mediator, lipopolysaccharide, disrupted BBB integrity *in vivo* and was associated with pericyte detachment from the basement membrane of the BBB (76). Confirmation of this trend will be attempted via electron micrographic or other nonimmunologic methods to ensure that increased pericyte density, rather than their accessibility to antibodies, is observed. These data provide insight into a potentially new therapeutic target to improve brain metastasis drug delivery.

Brain metastases represent an important clinical problem. In breast cancer, brain metastases are occurring when patients are either responding to systemic therapies or have stable disease, and threaten to limit the gains made in improved systemic chemo- and molecular therapies. It is probable that as systemic chemotherapy improves for other types of cancers, brain metastases will become even more widespread. Our results support a role of the BTB in hindering chemotherapeutic treatment of brain metastases for agents, such as paclitaxel and doxorubicin, that poorly penetrate the BBB. Further work is necessary to determine brain metastasis distribution of permeable chemotherapeutic agents. Given the failure of many poorly BBB-penetrable chemotherapeutic drugs, a new class of agents may be necessary for good chemotherapeutic activity against brain metastases. Such agents will need to be not only BBB permeable and active against metastatic breast cancer cells but also nontoxic to CNS constituents. Examples in the preclinical literature to date include lapatinib and vorinostat (49, 50). The concept of site-specific metastasis therapy represents a paradigm shift from a "one drug treats all sites" approach.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Acknowledgments

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