Harnessing Competing Endocytic Pathways for Overcoming the Tumor-Blood Barrier: Magnetic Resonance Imaging and Near-Infrared Imaging of Bifunctional Contrast Media

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Abstract

Ovarian cancer is the most lethal gynecologic malignancy, often diagnosed at advanced stage leading to poor prognosis. In the study reported here, magnetic resonance imaging and near-infrared reflectance imaging were applied for in vivo analysis of two competing endocytic pathways affecting retention of bifunctional daidzein-bovine serum albumin (BSA)-based contrast media by human epithelial ovarian carcinoma cells. Suppression of caveolae-mediated uptake using nystatin or by BSA competition significantly enhanced daidzein-BSA-GdDTPA/CyTE777 uptake by tumor cells in vitro. In vivo, perivascular myofibroblasts generated an effective perivascular barrier excluding delivery of BSA-GdDTPA/CyTE777 to tumor cells. The ability to manipulate caveolae-mediated sequestration of albumin by perivascular tumor myofibroblasts allowed us to effectively overcome this tumor-stroma barrier, increasing delivery of daidzein-BSA-GdDTPA/CyTE777 to the tumor cells in tumor xenografts. Thus, both in vitro and in vivo, endocytosis of daidzein-BSA-GdDTPA/CyTE777 by ovarian carcinoma cells was augmented by albumin or by nystatin. In view of the cardinal role of albumin in affecting the availability and pharmacokinetics of drugs, this approach could potentially also facilitate the delivery of therapeutics and contrast media to tumor cells.

Introduction

Ovarian cancer is the most lethal gynecologic malignancy, placing it among the five most common causes of cancer-induced deaths in women. Ovarian cancer is often detected at advanced stage, and despite frequent effective response to initial chemotherapy, clinical prognosis is poor (1). We have previously reported the contribution of luteinizing hormone and follicle-stimulating hormone in induction of angiogenesis and adhesion of ovarian carcinoma tumors (2). Furthermore, using magnetic resonance imaging (MRI), we showed that angiogenesis and progression in ovarian carcinoma is tightly linked spatially and temporally with stroma fibroblasts by MRI (9, 10). Due to the central role of albumin in affecting the pharmacokinetics of chemotherapeutics and contrast media, we evaluated the fate of bifunctional GdDTPA extravasated from leaky blood vessels in ovarian carcinoma tumor xenografts. Histologic staining of the biotinylated albumin-based contrast material showed lymphatic clearance, along with residual prolonged retention within the myofibroblast stroma tracks, where it was internalized by α smooth muscle actin expressing myofibroblasts. Subsequent in vitro studies showed that bifunctional GdDTPA was effectively internalized by fibroblasts using caveolae-mediated uptake, which could be suppressed by treatment with nystatin (9, 11). Upon internalization, the material is sequestered within small intracellular vacuoles leading to suppressed MRI relaxivity, which is regained only after the material is redistributed in the cells with cell division (9, 12). The contrast material did not extravasate into the interstitial space within the tumor nodules (9). The exclusion of the contrast media from the tumor nodules suggested that interaction of therapeutics or contrast media with albumin could significantly hinder their delivery to the tumor cells.

In the study reported here, we aimed to alter the distribution of bifunctional GdDTPA, and to enhance the partition of the contrast material to the tumor by addition of daidzein as a targeting ligand, recently reported to show high affinity to the ovarian carcinoma cells (13). A carboxyalkyl derivative of the isoflavone daidzein was used because isoflavones interact weakly with the estrogen receptors (ER) and have additional cellular activities not ascribed to activation of the ERs, such as regulation of cell-signaling pathways, and can inhibit proliferation and induce apoptosis in ER-negative breast cancer cell lines (e.g., MDA-MB-231), as well as in ER-positive lines (e.g., MCF-7; ref. 14). It was recently reported that the N-t-Boc-hexylenediamine derivative of 7-(O)-carboxymethyl daidzein exhibits more potent inhibitory activity on the growth of estrogen-sensitive (e.g., ovarian, colon) cancer cell lines than the parent isoflavones while retaining no estrogenic activity. As recently reported, the antiproliferative effects of this compound was also effective in vivo in reducing growth of human ovarian xenografts in nude mice (15). Daidzein-BSA-GdDTPA/CyTE777 conjugate was generated and applied here for MRI/near-infrared (NIR) detection of ovarian carcinoma tumors in vivo, whereas daidzein-BSA-FAM and BSA-ROX were used for in vitro analysis of endocytosis of the contrast media by fluorescence microscopy and by flow cytometry. This work adds daidzein to a rapidly growing list of ligands that are being developed for targeted imaging of tumors by MRI, including targeting glutamine transporters (16), folate receptors (17), and Her-2/neu receptors (18).

We report here that the use of daidzein-BSA-GdDTPA/CyTE777 (or FAM) as a bifunctional-targeted contrast media revealed a novel...
mechanism regulating endocytosis by ovarian cancer cells, involving competition between receptor-mediated internalization through binding of daidzein and caveolae-mediated internalization via binding of albumin. Thus, internalization of daidzein-BSA-GdDTPA/CyTE777 (or FAM) could be induced by competition with BSA CyTE777 (or ROX), or alternatively by inhibition of caveolae uptake using nystatin. Histologic analysis of tumors revealed significant uptake of the bifunctional contrast media to the tumor cells, overcoming the limited distribution observed for biotin-BSA-GdDTPA, which is restricted to the perivascular stroma cells. These results provide a mechanism for altering the microdistribution and partition of the contrast media within the tumor, achieving effective targeting of the tumor cells, and providing possibilities for modulating the delivery through exogenous competition with caveolae mediated binding of albumin.

Materials and Methods

Reagents

Bovine serum albumin (BSA), nystatin, polylysine, DTPA anhydride, GdCl₃, and 4,6-diamidino-2-phenylindole (DAPI) were purchased from Sigma-Aldrich. FAM-NHS and ROX-NHS were purchased from Molecular Probes, Invitrogen. N-1-(p-iodohippuranilophenyl) diethylenetriamine-N,N',N'-tetraacetate (DTPA), chelated with Eu⁺³ (EuDTPA) and enhancement solution were obtained from Perkin-Elmer. Goat-anti-rabbit peroxidase and goat anti-mouse peroxidase were obtained from Zymed. Rabbit anti-caveolin1 antibody was purchased from Santa Cruz.

Contrast Media

Daidzein-BSA-GdDTPA. BSA-DTPA was synthesized as described (19). Briefly, 1.5 grams of DTPA anhydride (suspended in 4 mL of dry DMF) were slowly added with stirring to 1.3 grams of BSA (in 40 mL Hepes 0.1M [pH 8.8]) while the reaction was titrated with NaOH 5N and stirred for 2 h. The product was dialyzed against NaHCO₃. Afterwards, the N-hydroxysuccinimide ester of 7-(O-carboxymethyl) (daidzein-NHS), synthesized according to reference (15), (11 mg in 800 µL of anhydrous DMF) was added to BSA-DTPA (in 40 mL of NaHCO₃ 0.1M [pH 8.5]) and stirred overnight. The product was dialyzed (19) first against NaHCO₃, followed by sodium citrate [0.1 M (pH 6.5)]. GdCl₃ [650 mg in 5 mL sodium acetate 0.1M (pH 6.0)] was added to daidzein-BSA-DTPA in sodium citrate [0.1 M (pH 6.5)]. The final product (daidzein-BSA-GdDTPA) was dialyzed extensively against water and lyophilized.

BSA-CyTE777/FAM/ROX. CyTE777-NHS (44 mg) prepared according to (20) or FAM-NHS (35 mg) or ROX-NHS (35 mg in 200 µL dry DMF) were added to BSA [450 mg in 15 mL NaHCO₃ 0.1M (pH 8.5)], slowly with stirring. The reaction was stirred overnight, and the product was dialyzed against NaHCO₃ 0.1M (pH 8.5), followed by several changes of water and lyophilized.

Daidzein-BSA-CyTE777/FAM. Daidzein-NHS (8 mg; in 600 µL dry DMF) was added to BSA-CyTE777/FAM [100 mg in 6 mL of NaHCO₃ 0.1M (pH 8.5)], and the reaction was stirred overnight. The product was purified by dialysis against NaHCO₃ 0.1M (pH 8.5), followed by several changes of water and lyophilized. This product was used for the in vivo studies.

Fluorescence microscopy. MLS cells (2×10⁶) were cultured on polylsine coated coverslips for 48 h. Subsequently, the coverslips were incubated for 1 h at 37°C with daidzein-BSA-FAM (200 µg/mL) or BSA-FAM (200 µg/mL) or combination of both (daidzein-BSA-FAM with BSA-FAM) in the presence or absence of a blocking dose of nystatin (50 µg/mL). The excess of fluorescent material was washed thrice with PBS, and the cells were fixed with 4% PFA, then washed, and stained with DAPI and mounted. The images were monitored by two-photon microscopy (2PM; Zeiss LSM 510 META NLO; equipped with a broadband Mai Tai-HP-femtosecond single box tunable Ti-sapphire oscillator, with automated broadband wavelength tuning 700–1,620 nm from Spectraphysics, for two-photon excitation). Histologic sections of isolated tumors, from mice injected with daidzein-BSA-FAM or combination of daidzein-BSA-FAM and BSA-FAM, were deparaffinized, stained with DAPI, and mounted. The fluorescence signal was monitored by confocal microscopy (Zeiss LSM 710).

Flow cytometry. MLS cells (1×10⁶) were incubated for 30 min with daidzein-BSA-FAM (200 µg/mL) or BSA-Rox (200 µg/mL) or a combination of both in the presence or absence of a blocking dose of nystatin (50 µg/mL). The excess of fluorescent material was washed thrice with PBS containing 0.01% of sodium azide. The cellular uptake of fluorescent material was monitored by FACScan. The excitation produced by air-cooled argon laser 288 nm and the emission signal was collected by FL1 filter (BP530/30) for FAM and FL2 filter (BP585/42) for ROX.

Animal experiments. All animal experiments were approved by the Animal Care and Use Committee of Weizmann Institute. CD-1 nude mice were inoculated s.c. with 2.5 × 10⁶ MLS tumor cells. Tumors were allowed to grow until 5 to 7 mm in diameter (approximately 14–21 d). In vivo NIR imaging. Tumor-bearing mice were injected with daidzein-BSA-CyTE777 [1×: 1 mg (for IVIS 100) or 0.5 mg (for IVIS Spectrum) in 0.1 mL PBS/mouse; n = 5 and n = 2, respectively], or with BSA-CyTE777 (1 or 0.5 mg in 0.1 mL PBS/mouse; n = 2 and n = 2) as control, or with daidzein-BSA-CyTE777 + BSA-FAM (1 mg (for IVIS 100) or 0.5 mg (for IVIS Spectrum) of each dye in 0.1 mL PBS/mouse; n = 2 and n = 2, respectively; for the BSA overload experiment). The NIR signal in the whole animal was monitored by IVIS 100 and IVIS Spectrum (Xenogen, Caliper) at 24, 48, and
72 h. The mice were fed with alfalfa-free (chlorophyll-free) diet 72 h previsualization. In the IVIS, 100 the data were acquired by 710 to 760 excitation, 675 to 720 excitation background, and 810 to 860 emission filters. In the IVIS Spectrum, the data obtained for the daidzein-BSA-Cy777 was acquired by 745 nm excitation and 820 nm emission filters.

The pharmacokinetics of the fluorescent and MRI BSA-based contrast media and their plasma concentration after i.v. administration were previously reported to be similar for all tags (19).

MRI measurements. MRI experiments were performed on a horizontal 4.7 T Biospec spectrometer using an actively radiofrequency decoupled 1.5-cm surface coil embedded in a Perspex board and a birdcage transmission coil. In vitro, $R_1$ measurements spin-echo images were acquired at 8 different repetition times ranging between 2,000 and 100 ms (2 averages; field of view, $4 \times 4$ cm; slice thickness, 1 mm; matrix $128 \times 128$). $R_1$ relaxation rates for the in vitro experiments were derived by nonlinear single exponential fitting of images acquired at different repetition times (equation [1]):

$$I = M_0(1 - e^{-TR/R_1})$$  \hspace{1cm} [1]

Where $I$ is the measured signal intensity for each $TR$, and $R_1$ was derived from optimization of the curve fitting; $M_0$ is the steady-state signal intensity in fully relaxed images.

In vivo. The tumor-bearing mice were injected i.v. with BSA-GdDTPA (12 mg in 200 μl PBS/mouse) or daidzein-BSA-GdDTPA (12 mg in 200 μl PBS/mouse) or with combination of daidzein-BSA-GdDTPA and BSA-FAM (competition experiment). $R_1$ was measured 24, 48, and 72h after injection of the contrast material. $T_1$-weighted three-dimensional gradient-echo images, with pulse flip angles of 5°, 15°, 30°, 50°, and 70° were acquired to determine the $R_1$ values. The acquisition parameters were as follows: $TR$, 10 ms; TE, 3.561 ms; 2 averages; field of view, $4 \times 4 \times 4$; 128 $\times 128 \times 128$ pixels. Three-dimensional gradient-echo data sets were used for generation of $R_1$ maps as well as for calculation of the average $R_1$ values in selected regions of interest by nonlinear best fit to equation [1]:

$$I = M_0\sin(x)(1 - e^{-TR/R_1})/(1 - \cos(x)e^{-TR/R_1})$$  \hspace{1cm} [2]

Where $I$ is the signal intensity as a function of the pulse flip angle. Student's $t$ test (two tailed, equal variance) was used for statistical analysis of the significance of change in relaxation rate between control and labeled tumors.

Results

Presence of caveolin 1 in MLS ovarian cancer cells. When MLS ovarian cells were subjected to SDS-PAGE and probed with an anti caveolin-1, a protein band of 21 kd was visualized by enhanced chemiluminescence (Amersham). MCF7-CV1 cells used a positive control showed a protein band with the same MW (Supplementary Fig. S1).

Albumin and daidzein-mediated labeling of ovarian carcinoma cells: fluorescence microscopy. Endocytic pathways in ovarian cancer cells were evaluated in vitro using two fluorescent probes, monofunctional BSA-FAM, targeting cellular caveolae (9), and bifunctional daidzein-BSA-FAM targeting both caveolae and cell surface receptors with affinity to daidzein. Binding and uptake of BSA-FAM and daidzein-BSA-FAM by MLS human epithelial ovarian carcinoma cells could be detected by fluorescence microscopy, showing internalization of the fluorescent probes into intracellular vesicles (Fig. 1A). Suppression of caveolae-mediated uptake by treatment of the cells with nystatin (50 μg/mL; 30 min), resulted, as expected, in an elevated membrane staining and reduced uptake of BSA-FAM (Figs. 1 and 2). Surprisingly, nystatin treatment resulted in significantly enhanced internalization of daidzein-BSA-FAM by MLS cells (Fig. 1). Thus, albumin binding mediated by caveolae seemed to interfere with internalization of daidzein-BSA-FAM into the cells, despite the role of caveolae uptake of BSA-FAM. To test this hypothesis, we evaluated the ability of BSA to compete with daidzein-BSA-FAM on the albumin binding site in caveolae, thereby facilitating internalization of the material to cells (Fig. 2). Here again, internalization of daidzein-BSA-FAM was augmented by addition of nystatin.

Albumin and daidzein-mediated endocytosis and labeling of ovarian carcinoma cells: flow cytometry. The binding and uptake of BSA-ROX and daidzein-BSA-FAM by MLS ovarian carcinoma cells was quantified by flow cytometry (Fig. 3). MLS cells were incubated with either BSA-ROX, daidzein-BSA-FAM, or with both BSA-ROX and daidzein-BSA-FAM in the presence or absence of nystatin. Treatment with nystatin resulted in a significant 4-fold enhancement in the fluorescence intensity of cells incubated with daidzein-BSA-FAM (Fig. 3A and B). On the other hand, binding and uptake of BSA-ROX were only slightly reduced by nystatin. These results are consistent with a shift from...
Endocytosis to membrane binding of daidzein-BSA-FAM in the presence of nystatin as detected by fluorescence microscopy (Fig. 1). Incubation of the cells with both BSA-ROX and daidzein-BSA-FAM resulted in a differential response to nystatin, with increased labeling of cells with daidzein-BSA-FAM (3-fold induction in the intensity and increase of 20% in the population of labeled cells), and decreased fluorescence of BSA-ROX (1.3-fold decrease in intensity and 51% decrease in labeled population; Fig. 3B–D). These results are also consistent with the endocytic pathways detected by fluorescence microscopy (Fig. 1).

In vivo fluorescence imaging of targeted delivery of daidzein-BSA-CyTE777 to ovarian carcinoma. Systemic delivery of daidzein-BSA-CyTE777 resulted in tumor selective enhancement of NIR fluorescence for subcutaneous ovarian carcinoma tumor xenografts (Fig. 4). Mice were inoculated s.c. with $2.5 \times 10^6$ MLS tumor cells. Ten days after tumor inoculation, mice were given daidzein-BSA-CyTE777 alone, suggesting that the endogenous level of albumin may be better optimized for targeted imaging, and BSA overload could reduce specificity by interference with clearance pathways. Consistent with our hypothesis, we observed different pharmacokinetic behavior in the elimination of the contrast materials from the tumor. Control mice injected with BSA-CyTE777 showed first order clearance of the contrast media. Daidzein-BSA-CyTE777 was eliminated with rapid initial kinetics, faster than the elimination rate of BSA-CyTE777. However, this was followed by residual retention of daidzein-BSA-CyTE777 with very slow clearance. Thus, after the initial elimination, mice that were given daidzein-BSA-CyTE777 showed a specific NIR signal in the tumor area that retains for 48 hours after the administration ($n = 7$), and it was statistically significant comparing to the signal of the BSA-CyTE777 injected mice ($n = 4$; $P = 0.047$; Fig. 4B). The NIR signal in the tumors was detectable even 10 days after the administration.
Biodistribution of Daidzein-BSA-EuDTTA (chelate). The lanthanide chelate of europium (Eu³⁺; analogue to GdDTPA) has unique fluorescence properties allowing its use for labeling antibodies in immunoassays. MLS tumor–bearing mice were injected with BSA-Eu chelate (n = 3) or daidzein-BSA-Eu chelate (n = 5). After 24 or 48 hours, the mice were sacrificed and the tumors were isolated. The fluorescence due to Eu in the various extracts of tissues was determined. A large 2- to 3-fold increase in Eu was detected in tumors of the mice injected with daidzein-BSA-Eu chelate compared with those injected with BSA-Eu chelate at 24 and 48 hours after injection (Supplementary Fig. S2).

Distribution of daidzein-BSA-FAM in ovarian tumors. The distribution of contrast material inside the tumors was visualized by fluorescence microscopy, in tumors isolated 24 hours after injection with daidzein-BSA-FAM or BSA-FAM. Daidzein-BSA-FAM was localized in the tumor cells areas, whereas BSA-FAM was localized to the tumor blood vessels and their surrounding stroma cells (Fig. 5A–B).

Additionally, we observe different distribution pattern of daidzein-BSA-FAM or BSA-ROX in the tumor isolated 24 hours after their combined injection. Consistent with our previous results, daidzein-BSA-FAM was distributed in all the tumor area with enhanced staining around the vessel, whereas BSA-ROX was localized to the stromal fibroblast area. (Fig. 5C).

In vivo MRI detection of targeted delivery of Daidzein-BSA-GdDTPA to ovarian carcinoma. Daidzein-BSA-GdDTPA showed significant relaxivity of 194 mM⁻¹s⁻¹ (per BSA; Fig. 6A). This relaxivity was similar to the relaxivity of BSA-GdDTPA 196 mM⁻¹s⁻¹ (per BSA).

MRI data acquired from MLS tumor–bearing mice 24 hours after administration of daidzein-BSA-GdDTPA or BSA-GdDTPA (12 mg/200 µL; n = 5–7 per group), showed significantly higher contrast enhancement, consistent with accumulation of daidzein-BSA-GdDTPA in the tumor site compared with vehicle-injected mice or mice injected with BSA-GdDTPA (Fig. 6B). Time course experiments showed specific localization and retention of targeted contrast agent (daidzein-BSA-GdDTPA; n = 7) in the tumor site 24 (Fig. 6C).

Prolonged detection of the targeted contrast material was feasible even for a lower administered dose. MLS tumor–bearing mice were injected with daidzein-BSA-GdDTPA (4 mg/200 µL; n = 3). The specific localization of the targeted contrast agent in the tumor site was detected by MRI at 9.4T 24 hours after injection and was still detectable and even enhanced 7 days after injection (Fig. 6D, arrows).

The effects of BSA overload were studied on MLS tumor–bearing mice injected with daidzein-BSA-GdDTPA (4 mg) or combination of daidzein-BSA-GdDTPA and BSA-FAM. R1 of the tumor area was monitored after 24 hours. Elevation in R1 was observed for the tumor from animal injected with combination of daidzein-BSA-GdDTPA and BSA-FAM compared with the control animals (Supplementary Fig. S3).

Discussion

Despite the high permeability tumor neovasculature to plasma proteins, targeting of contrast media and delivery of therapeutics to tumors is frequently compromised leading to poor sensitivity for tumor detection and resistance to therapy. The low transfer rate was attributed to high interstitial pressure, and indeed a number of studies reported improved delivery with vascular normalization induced by antiangiogenic therapy (21), or alteration of extracellular matrix using hyaluronidase (22).

In the study reported here, we explored yet another mechanism for tumor escape from delivery of extravasated albumin-based contrast media, through caveolae-mediated sequestration of the contrast material by perivascular myofibroblasts, thus generating an effective tumor-blood barrier. Evoking alternate competing endocytic pathway using daidzein resulted in significant partition of the contrast material into the tumor, which could be further enhanced through suppression of caveole-mediated endocytosis by competition with albumin.

The phytoestrogen daidzein bound to BSA was used here as a macromolecular bifunctional contrast agent targeting ovarian carcinoma cells. In vivo imaging of daidzein-BSA-GdDTPA/ CyTE777 allowed MRI and NIR imaging detection and analysis of the interaction between endocytic pathways in MLS human epithelial ovarian carcinoma xenografts.

The in vitro use of carboxy derivatives of isoflavones as carriers for affinity targeting of drugs to tumor cells expressing estrogen receptor of the β type was recently reported (13, 15, 23). Acting as a weak estrogen, daidzein may recognize a putative plasma membrane estrogen receptor and a membrane-located estrogen receptor β–related protein. Additionally, daidzein was reported to interact with the lipid interface on the cell surface (24), thus facilitating endocytosis. It has been reported that caveolin-1 colocalizes with plasma membrane estrogen receptor in lipid rafts.
Gilad and colleagues (26) reported the importance of caveolin-1 in the compartmentalization of estrogen receptor to the membrane, allowing 17β-estradiol (E2) to control vitamin D receptor transcription and expression. Daidzein could interact also with raft-located estrogen receptor like protein that did not cointeract with calveolae (27).

As reported here, MLS human epithelial ovarian carcinoma cells express low levels of caveolin-1 that can mediate the BSA uptake to the MLS cells. As expected, inhibition of caveolae uptake using nystatin suppressed cellular internalization of fluorescently tagged BSA, and changed the pattern of cellular localization of this agent, leading to membrane staining and inhibition of endocytosis.

Cellular uptake of daidzein-BSA-FAM and BSA-ROX alone and in combination showed segregation of the labels, suggesting independent uptake pathways for daidzein-BSA and BSA. Surprisingly, nystatin significantly augmented the cellular uptake of daidzein-BSA-FAM, whereas the uptake of BSA-ROX was slightly suppressed by nystatin along with a shift toward membranal localization, suggesting that although daidzein-BSA-FAM is internalized through a caveolae-independent endocytic pathway, its uptake can be attenuated by the interaction of BSA with caveolin. Similar to the effect of nystatin, administration of BSA-ROX effectively increased daidzein-BSA-FAM uptake. These results are consistent with the presence of two competing and mutually exclusive endocytic pathways for daidzein-BSA-FAM, where one of them is BSA mediated and caveoleae dependent, and the second is daidzein mediated and caveolae independent.

In vitro, NIR imaging showed specific localization and prolonged retention of daidzein-BSA-CyTE777 in ovarian carcinoma tumors, compared with BSA-CyTE777. Similarly elevated enhancement of tumors was observed by MRI for daidzein-BSA-GdDTPA relative to BSA-GdDTPA, and contrast media retention in the tumors could be detected up to 7 days after administration of the contrast media. Enhancement of contrast seemed to develop with time after administration. Such behavior is consistent with quenching of relaxivity upon internalization of the contrast media with subsequent enhancement of relaxivity with cell proliferation and intracellular redistribution of the contrast media. Such changes in contrast media relaxivity were previously reported by us for endocytic uptake of BSA-GdDTPA (9, 10, 19).

In accord with the in vitro results, it is important to consider that retention of the NIR signal in the tumor area is amplified by the intrinsic competition with the endogenous mouse albumin that can compete with daidzein-BSA for uptake by caveolae. Furthermore, uptake of daidzein-BSA could be further amplified by exogenously delivered BSA overload. Further analysis is required to establish the optimal concentration of albumin required for maximal delivery of daidzein-BSA. Importantly, hypoalbuminemia (28), a common complication in patients with advanced cancer (29) and a major side effect of some chemotherapeutic agents (30–33), can affect the delivery of daidzein-BSA, and thus supplementation with exogenous albumin should be considered.

Histologic analysis revealed a major difference in the distribution of daidzein-BSA-GdDTPA and BSA-GdDTPA in tumors. Effective distribution of daidzein-BSA-FAM was observed inside the tumor nodules, whereas BSA-FAM was predominantly localized within blood vessels and in the perivascular tumor stroma myofibroblasts as reported previously (10).

The study reported here was performed on subcutaneous tumor xenografts that are typically characterized by extensive fibrous reaction. This choice of model facilitated quantification of the contrast media. However, the clinical relevance of the model is nevertheless clear, as extensive involvement of stroma is common
to many human carcinomas. Fibroblast involvement was reported for the supportive stroma of breast (34, 35) and prostate (36, 37) carcinomas, contributing to angiogenesis (38), abnormal composition of extracellular matrix (39), and fibrosis development (40).

Targeting caveolae was suggested previously as a mechanism for facilitation of transendothelial transfer so as to improve delivery of therapeutics to tumors (41, 42). Similar to albumin-bound (nab) paclitaxel (nab-paclitaxel; Abraxane; refs. 43, 44) that was recently approved for use in patients with metastatic breast cancer (45), daidzein-BSA shows enhanced endothelial cell transcytosis (44), enhanced permeability and retention effect, and prolonged half-life time in the plasma. In addition, daidzein-BSA shows specific affinity to ovarian cancer cells, using intrinsic competition with albumin for saturating the caveolae pathway and enhancing tumor cell uptake. Interestingly, fluorescently labeled Abraxane showed limited partition to the tumor cells and significant perivascular accumulation, suggesting possible uptake by perivascular stroma cells (46).

In summary, we reported here the use of MRI and NIR imaging for in vivo dissection of two independent endocytic pathways affecting contrast media retention by human epithelial ovarian carcinoma cells. As shown here, daidzein-BSA-GdDTPA/Cy7 can potentially facilitate the detection of ovarian tumor lesions and metastasis, further research is required for validating the ability to detect targeted contrast media for peritoneal metastases. Based on previous reports, this system potentially may be used for detection of other types of cancer that are daidzein sensitive, including prostate (47, 48) and breast (49, 50). The mutually exclusive competing mechanisms for daidzein and BSA-mediated uptake could be further exploited for augmenting the selective targeted delivery of therapy to ovarian carcinoma cells through suppression of caveolae binding. Moreover, the ability to manipulate caveolae-mediated internalization allowed us to effectively overcome the tumor-blood barrier mediated by caveolae sequestration of albumin in perivascular tumor myofibroblasts, thus augmenting delivery of the contrast media to the tumor cells. In view of the cardinal role of albumin in affecting the availability and pharmacokinetics of drugs, this approach could potentially also facilitate the delivery of therapeutics to tumor cells.

Disclosure of Potential Conflicts of Interest

M. Neeman, F. Kohen, and H.S. Migalovich have applied for a patent for the use of daidzein-BSA-GdDTPA for targeted imaging of cancer. The other authors declared no potential conflicts of interest.

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MIR and NIR Imaging of Daidzein-BSA-GdDTPA/CyTE777

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