**Novel Recombinant Human B7-H4 Antibodies Overcome Tumoral Immune Escape to Potentiate T-Cell Antitumor Responses**

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**Abstract**

B7-H4 (VTCN1, B7x, B7s) is a ligand for inhibitory coreceptors on T cells implicated in antigenic tolerization. B7-H4 is expressed by tumor cells and tumor-associated macrophages (TAM), but its potential contributions to tumoral immune escape and therapeutic targeting have been less studied. To interrogate B7-H4 expression on tumor cells, we analyzed fresh primary ovarian cancer cells collected from patient ascites and solid tumors, and established cell lines before and after in vitro passaging. B7-H4 expression was detected on the surface of all fresh primary human tumors and tumor xenotransplants, but not on most established cell lines, and B7-H4 was lost rapidly by tumor xenograft cells after short-term in vitro culture. These results indicated an in vivo requirement for B7-H4 induction and defined conditions for targeting studies. To generate anti-B7-H4–targeting reagents, we isolated antibodies by differential cell screening of a yeast-display single-chain fragments variable (scFv) library derived from patients with ovarian cancer. We identified anti-B7-H4 scFv that reversed in vitro inhibition of CD3-stimulated T cells by B7-H4 protein. Notably, these reagents rescued tumor antigen-specific T-cell activation, which was otherwise inhibited by coculture with antigen-loaded B7-H4+ APCs, B7-H4+ tumor cells, or B7-H4-tumor cells mixed with B7-H4+ TAMs; peritoneal administration of anti-B7-H4 scFv delayed the growth of established tumors. Together, our findings showed that cell surface expression of B7-H4 occurs only in tumors in vivo and that antibody binding of B7-H4 could restore antitumor T-cell responses. We suggest that blocking of B7-H4/B7-H4 ligand interactions may represent a feasible therapeutic strategy for ovarian cancer.

Cancer Res; 73(15); 1–10. ©2013 AACR.

**Introduction**

Tumor-associated macrophages (TAM) inhibit antitumor immune responses through the release of humoral mediators and also protect tumors from immune recognition by hampering cell-mediated immune responses through the cell surface expression of inhibitory molecules such as B7-H4 (1). TAMs derive from resident macrophages or from monocytes recruited by the tumor microenvironment and polarized at the tumor site (2). Tumor infiltration with TAMs has been associated with poor patient survival (3) and targeting TAMs represents a promising strategy against cancer. Several approaches have already been developed, including depletion with clodronate liposomes (4), tumor recruitment inhibition by CSF-1R and CCL2 targeting (5), and "reeducation" through activation via anti-CD40 monoclonal antibody (mAb; ref. 6), or HRG plasma protein (7), or mannose receptor (8).

B7-H4, also called B7x/B7s, is B7 superfamily member, recently identified as an inhibitory modulator of T-cell response (9–11). When present at the surface of antigen-presenting cells (APC), B7-H4 negatively regulates T-cell activation, possibly through interaction with a ligand that remains to be identified (12). Consistent with this observation, B7-H4 adenoviral overexpression in pancreatic islets protects mice from autoimmune diabetes by maintaining peripheral tolerance (13), whereas B7-H4 knockout mice are more resistant to *Listeria monocytogenes* infection than their wild-type littermates (14). B7-H4 mRNA is widely expressed but the restricted pattern of protein expression in normal tissues suggests post-transcriptional regulation. B7-H4 expression in tumor tissues is observed in various types of human cancers such as breast (15), ovarian (1), pancreatic, lung (16, 17), melanoma (18), and renal cell carcinoma (19). In most studies, B7-H4 was determined to be either located in the cytoplasm or at the plasma membrane protein by immunohistochemistry (18–22). In ovarian cancer cell lines, B7-H4 expression was also reported to be mainly intracellular by flow cytometry (1, 16). A soluble form of...
B7-H4 is also detected in blood samples from patients with cancer (23, 24). The broad presence of B7-H4 in various cancers and its known function as negative regulator of T-cell activation suggest a specific role in downregulation of antitumor immunity. In fact, ovarian cancer-derived B7-H4+ TAMs suppress HER2-specific T-cell proliferation and cytotoxicity, and the blocking of B7-H4 expression on macrophages using morpholino antisense oligonucleotides improved tumor-associated antigen T-cell responses in vitro and in vivo (1). Altogether, these results ascribe a translational value to B7-H4 as a target molecule for antitumor immunotherapy. However, the clinical use of antisenses remains limited because of low stability in vivo due to serum inactivation, enzymatic degradation, and innate immune activation, and of the lack of specific targeting and rapid elimination when oligonucleotides are delivered in a naked form (25). Alternate means for blocking B7-H4 activity thus require further development for clinical applications. Cell surface targeting could improve specificity, but cell surface expression of B7-H4 in ovarian cancer remains unclear. Here, we studied B7-H4 cell surface expression on ovarian tumors and isolated novel anti-B7-H4 recombinant antibodies to target B7-H4. Single-chain fragments variables (scFv) are recombinant antibodies expressing single antigen-binding domain constituted by peptide-linked variable domains of heavy and light immunoglobulin chains. Small size, versatility, and amenability of scFvs to affinity maturation make them particularly interesting for in vivo targeting, in vivo imaging after conjugation with radioisotopes, and for therapeutic purposes after conjugation with endotoxins or nanoparticles (26) or fused to T-cell signaling domains to engineer modified T-cell receptors (TCR; ref. 27).

Here, we generated a yeast-display library of scFvs isolated from tumor-infiltrating B cells and peripheral blood mononuclear cells (PBMC) derived from 11 patients with ovarian cancer. Anti-B7-H4 scFvs were first selected for specific binding to both soluble B7-H4 recombinant protein (rB7-H4) expressed by mammary cells and B7-H4+ cancer cells, then screened for functional blocking of B7-H4–mediated T-cell inhibition. We generated in vitro systems to model T-cell inhibition upon binding of B7-H4 presented in cis or in trans, and we tested the ability of the newly isolated anti-B7-H4 scFvs to reverse nonspecific and antigen-specific T-cell inhibitions in vitro and in a humanized mouse model of ovarian cancer.

Materials and Methods

Human samples and ovarian cancer cell lines

Ascites and solid tumors samples from patients with ovarian cancer with advanced disease were obtained from the Ovarian Cancer Research Center’s patient sample repository of the University of Pennsylvania (Philadelphia, PA). Purified T cells and monocytes from healthy donors were obtained from the Human Immunology Core of the University of Pennsylvania. All specimens were collected under a University Institutional Review Board—approved protocol, and written informed consent was obtained from each donor.

T2 APC (174×CEM.T2), OVCAR3, MDA231 (HTB-26), and MDA468 (HTB-132) were obtained from American Type Culture Collection. M2 macrophages were generated as previously described (8). The human melanoma line 624 was provided by S.A. Rosenberg, National Cancer Institute (NCI)/NIH, (Bethesda, MD). EBV-B cells were kindly provided by Dr. Raj Somasundaram (Wistar Institute, Philadelphia, PA). A1847, OVCAR5, and C30 were tested by short tandem repeat profiling for validation.

Isolation of anti-B7-H4 scFvs from ovarian cancer-derived yeast-display scFv library

Anti-B7-H4 scFvs were first selected by magnetic and flow sorting using rB7-H4 versus control protein, as previously described (8, 28). The selected subpopulation of yeast-display scFvs was further selected by cell panning using a protocol derived from Wang and colleagues (29) with the following specifications: C30 ovarian cancer cells were transduced with pELNS-B7-H4 or with pELNS-GFP (negative control) and grown as monolayer on poly-L-lysine-coated dishes to 90% confluence. Yeast were induced to express scFv, washed, and depleted for nonspecific binders by 2 incubations with GFP+ C30 cells at a ratio of 30–60:1 yeast:cells for 30 minutes at room temperature with gentle rotation to prevent clumping. Unbound yeast were harvested and further incubated with plastic-immobilized B7-H4 C30 cells for 30 minutes at room temperature with gentle rotation. Plates were washed twice with PBS (5 minutes, room temperature) and examined under microscope. Yeast clusters binding to cells were harvested, grown in petri dishes O/N, and transferred into flasks for induction. Yeast panning was repeated four times. Yeast-displayed scFvs were finally converted into soluble forms as described in refs. 8, 28.

T-cell activation

B7-H4 inhibition of T-cell activation and proliferation was conducted using plate-immobilized recombinant B7-H4 protein and PBMCs from random, healthy donors. A day before T-cell activation, antibodies [anti-CD3 mAb (clone OKT3, 5 μg/mL) and/or anti-CD28 (eBiosciences, 2 μg/mL)] were plastic-immobilized O/N in 100 μL/well of bicarbonate buffer on flat 96-well tissue culture plates at 4°C. The antibody solution was removed on the day of T-cell activation and 10 μg/mL of rB7-H4 protein was coated in 100 μL per well of bicarbonate buffer for 2 hours at 37°C. A nonrelevant recombinant protein (FOLR1) was used as control. T cells were labeled with 3 μmol/L of CFSE (Invitrogen), washed, and distributed at 1×10^5 in 150 μL per protein-coated wells. Fifty microliters of 10 to 0.1 μg/mL of anti-B7-H4 scFvs were finally added. T-cell responses were analyzed 5 days after activation. Assays were conducted in triplicates.

T-cell cocultures

Wild-type, GFP–, or B7-H4–transduced T2 antigen-presenting cells (APC) were resuspended at 10×10^5 cells per mL and loaded with HER-2 or MART-1 peptides at various concentrations for 2 hours at 37°C. Cocultures of peptide-loaded APCs with HER-2 or MART-1 TCR-specific T cells were conducted at 1:1 ratio of 1×10^5 T2 APCs and 1×10^5 T cells, in 200 μL of RPMI medium in round-bottom 96-well tissue culture plates. MART-1 and HER-2 peptides were used...
as irrelevant peptides for the mock stimulations of HER-2 TCR T cells and MART-1 TCR T cells, respectively. Ten to 0.1 μg/mL of anti-B7-H4 scFvs were added and T-cell responses were analyzed after 2 days.

In vitro tumor-polarized TAM-mediated inhibition assays were conducted in Transwell cocultures in 24-well plates, with 1 x 10⁴ T2, 1 x 10⁵ T cells, and 1 x 10⁵ TAMs at 1:1:1 ratio. TAM polarization was achieved after Transwell coculture of macrophage colony-stimulating factor (M-CSF)- and granulocyte macrophage colony-stimulating factor (GM-CSF)-differentiated macrophages with OVCAR3 as described previously (8), with the following modifications: 5 μg/mL of anti-B7-H4 scFvs were added at day 0 and T-cell responses were analyzed after 3 days.

Breast cancer (MDA231, MDA468) and melanoma (624) cell lines were cocultured with antigen-TCR-specific T cells at 1:1 ratio (1 x 10⁵ tumor cells/1 x 10⁵ T cells) in 200 μL of RPMI media in presence of 5 μg/mL of anti-B7-H4 scFvs. T-cell responses were analyzed after 2 days. All assays were conducted in triplicates.

Statistical analysis
Statistical analyses were conducted with one-way ANOVA and unpaired t tests.

Results
B7-H4 cell surface expression on tumor cells is upregulated in vivo and downregulated by in vitro culture
Cell surface targeting requires the presence of specific extracellular domains. We analyzed B7-H4 cell surface expression by flow cytometry in established ovarian cancer cell lines (n = 4) and in ovarian cancer samples (ascites and solid tumors, n = 15) using commercially available antibody. As expected, cell surface expression of B7-H4 on established ovarian cancer cell lines was limited (Supplementary Fig. S2; ref. 16). In contrast, cell surface expression of B7-H4 was detected in all 15 fresh primary solid tumors and ascites samples, and a third of the tumors expressed B7-H4 on more than 29% and up to 57% of CD45/Epcamþ tumor cells (Fig. 1; Supplementary Table S1). Mean frequency of tumor cells expressing surface B7-H4 was 28% ± 17.9 in ascites and 12% ± 7.2 in solid tumors (Supplementary Table S1). B7-H4 cell surface expression on tumor-associated CD45⁺CD14⁺ macrophages was consistent with previous reports (1) and was associated with the coexpression of CD206/mannose receptor, a marker of mature M2 macrophages and of TAMs, in up to 30% of tumor ascites-associated CD45⁺CD14⁺ cells (Fig. 1C, gray triangles).

Figure 1. B7-H4 expression on primary human ovarian cancer cells and TAMs. B7-H4 cell surface expression in freshly harvested human ovarian cancer ascites and solid tumors was analyzed by flow cytometry after dead cells exclusion. Epcam staining characterized tumor cells, CD45 leukocytes (A and B), and CD45 CD14 macrophages (C). The percentage of macrophages expressing CD206 (TAMs) and/or B7-H4 was calculated upon gating on Epcam⁻CD45⁻CD14⁺ cells (top quadrants; A and B). Vertical scatter plots represent data obtained from ascites (n = 6) and solid tumors (n = 9). The mean of each group is indicated by the horizontal line.
To address whether surface expression of B7-H4 was inducible in vivo, we established intraperitoneal tumors in Balb/c nude mice using OVCAR5, a human ovarian cancer cell line with undetectable surface B7-H4 expression (Supplementary Fig. S2). Nine weeks after tumor inoculation, ascites and solid tumors were collected (n = 6) and analyzed for B7-H4 expression by flow cytometry. Figure 2 shows that cell surface expression of B7-H4 was upregulated in all freshly harvested OVCAR5 tumors, with positive expression ranging from 4% to 38% of CD45+ tumor cells (mean = 12.8% ± 5.2), but was restored to undetectable levels after short-term culture in vitro. Of note, in vitro culture of OVCAR5 cells in presence of interleukin (IL)-4 and/or IL-10 and/or TNFα at 10 μg/mL could not induce B7-H4 expression (data not shown). These results showed that surface expression of B7-H4 on human ovarian tumor cells is inducible in vivo, and is downregulated following in vitro cell culture.

**Generation of a yeast-display scFv library derived from tumor-associated B cells from patients with ovarian cancer for the isolation and validation of novel anti-B7-H4 scFvs**

The construction of yeast scFv display libraries has been described elsewhere (28). Briefly, we constructed a novel yeast-display library of recombinant antibodies (scFvs) derived from the variable regions of the heavy (VH) and light (VL) Ig chains, and fragments of B cells isolated from ascites (n = 10) and PBMCs (n = 1) of patients with ovarian cancer (Zhao A. and colleagues, manuscript in preparation). The insertion of VH and VL fragments in pAGA2 vector (28) was conducted by yeast transformation. The expression of VH and VL was confirmed by ELISA. The VH and VL were linked together by the linker GSGSRRRSSSSSGGGGSGGGGSSSGGGGGG (25, 30). The diversity of the library was estimated at 109. The process of soluble scFv isolation is recapitulated in Supplementary Fig.S3. Briefly, we first conducted a protein-based enrichment for anti-B7-H4 scFvs by 3 magnetic and 2 flow sortings of the yeast-display scFv library and we isolated a subpopulation of yeast-display scFvs that bound to soluble recombinant B7-H4 (rB7-H4) protein. The selected yeast-display scFv subpopulation was then shuffled into p416 BCCP yeast-secreting vector by homologous recombination, as previously described (28, 31, 32) to produce soluble scFvs. Screening for soluble anti-B7-H4 scFvs was conducted by 4 rounds of panning on a C30 ovarian cancer cell line transduced for cell surface expression of human B7-H4 or of GFP as negative control (cell-based screening strategy). Two soluble scFvs (26 and 56) directly issued from the protein-based enrichment and 2 scFvs (3#54 and 3#68) issued from the cell-based screening strategy, were selected for further analysis. Selected scFvs assayed by capture ELISA for binding to serial dilutions of rB7-H4 yielded similar results; BSA was used as control protein (Supplementary Fig. S4). ScFvs were sequenced and analyzed for their germline immunoglobulin gene usage of the predicted amino acid sequence by the Kabat system (Supplementary Table S2). Immunoglobulin gene usage comparison of protein-based isolated scFv clones 26 and 56 showed substantial differences in immunoglobulin gene usage in both heavy and light chains. ScFv clones 3#54 and 3#68 displayed different heavy chain immunoglobulin genes but had essentially similar light chains. Clones 26 and 3#68 shared the same IGHV and IGHJ genes but possessed different IGHJ genes for the heavy chains and different light chains.

**Anti-B7-H4 scFvs partially or fully block rB7-H4–dependent inhibition of polyclonal T-cell activation**

Normal donor T cells were stimulated with immobilized anti-CD3 with or without anti-CD28 antibody in the presence of soluble rB7-H4 or control protein (soluble recombinant alphafolate receptor). As expected, T cells stimulated by anti-CD3 antibody with or without anti-CD28 antibody secreted IFN-γ, expressed the activation marker CD69, and underwent cell division. In presence of plate-bound rB7-H4, IFN-γ secretion mediated by CD3 stimulation was inhibited (P = 0.032; Fig. 3A), as well as CD69 expression and T-cell proliferation assessed by carboxyfluorescein succinimidyl (CFSE) labeling (Fig. 3B). As...
rB7-H4 did not significantly inhibited T-cell IFN-γ secretion, proliferation, or CD69 expression mediated by a combination of anti-CD3 and anti-CD28 mAbs (P = 0.09), CD3-mediated T-cell stimulation was chosen to functionally characterize the potency of anti-B7-H4 scFvs in the remainder of our study.

Figure 4 shows that anti-B7-H4 scFvs could partially or fully reverse rB7-H4–mediated inhibition of polyclonal T-cell activation. Anti-B7-H4 scFv 3#68 fully restored T-cell IFN-γ secretion (P = 0.1305; Fig. 4A) and reversed rB7-H4–dependent inhibition of T-cell proliferation to control levels (Fig. 4B). Anti-B7-H4 scFvs 3#54 and 26 partially restored T-cell IFN-γ secretion (P = 0.0406 for 3#54; P = 0.1305 for 26; Fig. 4A) and scFv 3#54 reversed rB7-H4–dependent inhibition of T-cell proliferation to control levels (Fig. 4B); anti-B7-H4 scFv #56 did not have any impact on B7-H4–mediated T-cell inhibition. These results support the hypothesis that scFv interfering with functional interactions between B7-H4 and B7-H4 putative T-cell receptor can block B7-H4–dependent T-cell inhibition.

Antigen-specific T-cell activation is inhibited by peptide-pulsed antigen presenting cells expressing B7-H4 and restored by anti-B7-H4 scFvs

B7-H4 expression on tumor-infiltrated dendritic cells has been reported (33). To model B7-H4 function in a system of antigen presentation eliciting tumor antigen-specific T-cell responses, T2 APCs (T2; refs. 34, 35) were transduced to express the full-length human B7-H4 molecule (B7-H4+; T2; Fig. 5A), and peripheral human T cells were transduced to express TCRs specific for HLA-A2–restricted HER-2369–377 (Lanitis E. and colleagues, manuscript in preparation; Fig. 5B) or MART-126–35 epitopes (Fig. 5C; ref. 36). T2 transduced with GFP (GFP T2, gray bars) were used as negative controls (Fig. 5D and E). B7-H4+ T2 and GFP T2 were pulsed with MART-1 or HER-2 peptides and incubated with TCR-transduced T cells. IFN-γ secretion was measured by ELISA in culture supernatants. Figure 5B and C shows that B7-H4 expression on T2 (black bars) downregulated both antigen-specific T-cell activations (P = 0.0362 for HER-2 TCR T cells; P = 0.0024 for MART-1 TCR T cells), thus B7-H4–dependent inhibition was not antigen-specific. In addition, B7-H4–mediated inhibition of antigen-specific HER-2 TCR T-cell activation was partially reversed using anti-B7-H4 scFvs 56 (P = 0.132) and 3#54 (P = 0.086) and fully reversed using anti-B7-H4 scFv 3#68 (P = 0.574; Fig. 5D); scFv 3#68 could partially reverse B7-H4-mediated inhibition at concentration as low as 0.01 μg/mL (data not shown). Anti-B7-H4 scFv 3#68 also fully reversed B7-H4–mediated inhibition of antigen-specific MART-1 TCR T-cell activation (P = 0.2892; Fig. 5E). These results confirmed that antibody blocking of functional interactions between B7-H4+ T2 APCs and T cells could overcome B7-H4–dependent T-cell inhibition.

Anti-B7-H4 scFvs block third party inhibition of antigen-specific T cells mediated by tumor-polarized macrophages expressing B7-H4

Transwell coculture of macrophages with tumor cells produces tumor-polarized macrophages that express CD206 and B7-H4 (B7-H4 TAMs; refs. 8, 37). B7-H4 TAMs were tested for...
their ability to inhibit MART-1 TCR T cells stimulated with peptide-pulsed T2 APCs. Using the model system described in Fig. 5C (gray bars), we showed that the addition of B7-H4+ TAMs (Supplementary Fig. S5A, black bars) into cocultures of MART-1 TCR T cells with T2 APCs pulsed with MART-1 peptide (Supplementary Fig. S5A, gray bars) could downregulate IFN-γ secretion ($P = 0.0287$ for MART-1 at 2.5 nmol/L).

Activation and proliferation of antigen-specific T cells as measured by CFSE staining and CD137 expression were also inhibited by B7-H4+ TAMs, particularly at low peptide concentrations (Supplementary Fig. S5B and S5C). Anti-B7-H4 scFvs could reverse T-cell–inhibitory signals mediated by B7-H4+ TAMs; whereas anti-B7-H4 scFv 26 restored and significantly enhanced T-cell IFN-γ secretion by 1.5-fold ($P = 0.0148$; samples treated with scFv 26, $\gamma$, $P < 0.0019$; scFv 56, $\gamma$, $P < 0.0001$; scFv 3#54, $\gamma$, $P = 0.0406$; or scFv 3#68, $P = 0.1305$. NS, nonsignificant. Error bars represent SEM. B, flow cytometry analysis of CD69 T-cell expression and T-cell proliferation (CFSE dilutions), as indicated.

Antigen-specific T-cell activation is inhibited by tumor cells expressing B7-H4 and can be restored by anti-B7-H4 scFvs

Because B7-H4 can also be expressed on tumor cell surface in vivo (Fig. 1, Supplementary Table S1), we sought to address whether B7-H4+ tumor cells could inhibit antigen-specific T-cell function. HLA A2+ HER-2high MDA231 breast cancer and HER2low 624 melanoma cell lines (38) were transduced to express full-length B7-H4 (Fig. 6A and B) and used as targets for HER-2 TCR T cells. B7-H4 transduction did not affect the expression of HER-2 or HLA-A2 (data not shown). HLA A2+ HER-2neg MDA468 breast cell line (39) was used as a negative control for HER-2–specific T-cell activation. HER2high MDA231 cells triggered antigen-specific IFN-γ secretion by HER-2 TCR T cells (Fig. 6C and D), whereas HER2neg MDA468 cells (Fig. 6C) and HER2low 624 cells (Fig. 6D) could not or barely. IFN-γ secretion in response to MDA231 cells was significantly inhibited when MDA231 were transduced to express B7-H4 (B7-H4+ MDA231, $P = 0.0451$; Fig. 6C), and, as previously observed, anti-B7-H4 scFvs 3#54 and 3#68 further enhanced T-cell IFN-γ secretion by more than 2-fold ($P = 0.0037$ for scFv 3#54 and $P = 0.0061$ for scFv 3#68; Fig. 5F).

Treatment of humanized mice bearing ovarian cancer with anti-B7-H4 scFvs

To test anti-B7-H4 scFvs in vivo, we established a humanized mouse model of ovarian cancer by injecting subcutaneously...
OVCAR5 cells in NSG mice engrafted with a human immune system (HIS) derived from CD34^+ stem cells (HIS-NSG mice). We confirmed that tumor-infiltrating human macrophages and tumor cells expressed surface B7-H4 by flow cytometry (data not shown). HIS-NSG mice bearing established tumors (100 mm^2) were treated with anti-B7-H4 scFv 3#54 (n = 5; Fig. 7A) or 3#68 (n = 5; Fig. 7B). Tumor growth was delayed in 2 of 5 mice treated with anti-B7-H4 scFv 3#54 (Fig. 7A) and in all mice treated with anti-B7-H4 scFv 3#68 (Fig. 7B). Tumor infiltrations of CD3^+ cells were similar for the 2 groups (data not shown). These results were consistent with previous in vitro findings where anti-B7-H4 scFv 3#68 performed best to block B7-H4-mediated T-cell inhibition.

**Discussion**

B7-H4 expression in various types of human cancer tissues and its correlation with advanced stages, poor patient survival, and tumor infiltration by T regulatory cells (40), makes it a candidate of choice for targeted therapy. However, B7-H4 expression has been reported to be mainly intracellular for ovarian cancer cells (1, 16), which limits antibody use for targeted therapy. While confirming poor cell surface expression of B7-H4 on long-term cultured ovarian cancer cell lines, we found that B7-H4 was expressed at the surface of tumor cells freshly harvested from ascites and solid tumors of patients with ovarian cancer. Consistent with this observation, B7-H4
was expressed by tumor cells from freshly harvested ovarian cancer xenografts developed from B7-H4+/CO ovarian cancer cell lines and was fully downregulated after short-term in vitro culture. The expression of B7-H4 on both cell surfaces of tumor and tumor-infiltrating immunosuppressive cells establishes a new paradigm for simultaneous immunomodulation of the tumor microenvironment and direct ovarian cancer cell eradication using B7-H4-based targeting.

We thus isolated recombinant antibodies specific for human B7-H4 from a novel yeast-display scFv library derived from B cells of human ovarian cancer ascites and PBMCs. Selected anti-B7-H4 scFvs were evaluated for their functional ability to

Figure 6. B7-H4+ HER2+ tumor cells inhibit HER-2 TCR T-cell activation and anti-B7-H4 scFv 3#68 overcomes T-cell inhibition. A and B, flow cytometry analysis of B7-H4 cell surface expression with PE anti-B7-H4 mAb (open histogram) or isotype control (filled histogram) of HLA A2+ HER2high MDA231 cells, wild-type (WT MDA231), or B7-H4 transduced (B7-H4+ MDA231; A) and HLA A2+ HER2low 624 cells, wild-type (WT 624), or B7-H4 transduced (B7-H4+ 624; B), C and D, IFN-γ ELISA assays of HER-2 TCR T cells after stimulation with HER2neg MDA468 (light gray bar), WT MDA231 (dark gray bar), and B7-H4+ MDA231 (black bar) in culture medium, or WT 624 (white bars), B7-H4+ 624 (light gray bars), WT MDA231 (dark gray bars), or B7-H4+ MDA231 (black bars; D) in the presence of anti-B7-H4 scFvs, as indicated. One-way ANOVA analysis of IFN-γ T-cell secretion with WT 624, P = 0.3715; B7-H4+ 624, P = 0.0114; MDA231, P = 0.1726; B7-H4+ MDA231, and P = 0.0066.

Values for HER-2 TCR T cells cocultured with WT MDA231 vs. B7-H4+ MDA231 in medium, P = 0.0291; with B7-H4+ MDA231 in presence of scFv 26, P = 0.050; with scFv 56, P = 0.034; with scFv 3#54, P = 0.4393; with scFv 3#68, P = 0.2179. Error bars represent SEM.

Figure 7. Anti-B7-H4 scFv 3#68 delays ovarian cancer tumor growth in vivo. HIS-NSG mice bearing 100 mm3 subcutaneous tumors received 100 mg f anti-B7-H4 scFv 3#54 (n = 5; A) or 3#68 (n = 5; B), intraperitoneally, twice per week during 4 weeks, as indicated.
reverse T-cell inhibition mediated by rB7-H4 protein, by peptide-pulsed B7-H4- T2 APCs, by tumor-polarized B7-H4+ TAMs admixed with B7-H4+ tumor cells, and by B7-H4-transduced tumor cells. Our data show that the activation of tumor antigen-TCR–specific T cells can be inhibited by B7-H4 expressed either in cis on APCs or tumor cells, or in trans on TAMs (third party inhibition). In all cases, B7-H4–mediated inhibition could be partially reversed by anti-B7-H4 scFv clone 3#54 and fully restored by anti-B7-H4 scFv 3#68. Consistently, anti-B7-H4 scFv 3#68 showed better efficacy than anti-B7-H4 scFv 3#54 in delaying tumor growth; this suggests that scFv 3#68 could be useful when tumor immune responses preexist to therapy, as seen for targeted therapy directed against other immune checkpoint molecules such as CTLA-4, PD-1, or TIM-3. These results confirm that B7-H4 is a regulatory molecule engaged in negative signaling that impacts antitumor responses mediated by T cells. One possible trigger of B7-H4 surface expression could be hypoxic stress that is a common tumor microenvironment feature. However, hypoxic in vitro culture conditions did not upregulate B7-H4 cell surface expression in OVCAR5 cell line (data not shown). The cytokine milieu of the tumor microenvironment could be another possible mechanism. While Chen and colleagues, recently reported that macrophage-derived TNFα could induce B7-H4 cell surface expression in mouse lung carcinoma (41), in vitro culture of OVCAR5 cells in presence of IL4/IL10/TNFα did not induce B7-H4 expression (data not shown). These findings support the notion that B7-H4 cell surface expression may be regulated by environmental cues, possibly linking B7-H4 expression with enhanced tumor cell ability to escape immune recognition in vivo (42).

We used 2 strategies to isolate the anti-B7-H4 scFvs, one with conventional enrichment and selection by magnetic and flow sorting with B7-H4 recombinant protein and the other with differential cell panning added to the protein-based enrichment of the yeast-display scFv library (cell-based isolated scFvs). Analysis of scFv binding to recombinant B7-H4 by capture ELISA did not show any differences between the 2 approaches. However, cell-based isolated scFvs showed superior blockade capacity in functional assays. This suggests that differential cell panning permitted to select scFvs that bound to functional epitopes not available in recombinant antigens. As anti-B7-H4 scFv blockade in Transwell cocultures restored and enhanced MART-1 TCR T-cell responses in presence of B7-H4+ TAMs, we speculate that anti-B7-H4 treatment could also restore T helper 1 proinflammatory environment and further polarize macrophages into an M1-like phenotype that can then stimulate antigen-specific T cells. These results underscore the advantage of working with scFvs for in vivo targeting against functional epitopes. Random generation of scFv libraries eliminates the selection bias induced by in vivo immunization. In addition, working with scFv derived from human B cells reduces the risk for human antimurine antibody responses and in vivo inhibition by endogenous antibodies, and thus circumvents the need for costly and time-consuming antibody humanization. Finally, because the size of scFv is smaller than conventional antibodies, scFvs have an enhanced ability to penetrate tumor tissues. Together, our data show that anti-B7-H4 scFv possess promising functional blocking activity in vitro and their use in preclinical models of ovarian cancer is now warranted.

Ovarian cancer is a disease largely involving immune circuits that may predict better patient survival (43) or poorer outcome (40, 44). Targeting immune checkpoint molecules such as CTLA-4 and PD-1 has elicited strong clinical responses, especially in patients with preexisting immune responses (45–47). On the basis of our data, we propose that in vivo targeting of B7-H4 could simultaneously alter or destroy functionally diverse components of the tumor mass, including tumor cells and TAMs, thus potentiate T-cell–mediated antitumor responses.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were declared.

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Acknowledgments
The authors thank Andrew Best for his processing of human samples and Efthymia-Iliana Matthaiou for analyzing immunohistology slides.

Grant Support
The work was supported by the NCI FCCC-UPenn Ovarian Cancer SPORE (P50CA083638) Career Development Awards (N. Scholler and D.J. Powell), by the DOD OC110673 (N. Scholler), by the Ovarian Cancer Research Fund (PPD-PP-01.12) Project 2 (D.J. Powell), and by the Sandy follman Ovarian Cancer Foundation (D.J. Powell).

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Received September 4, 2012; revised April 23, 2013; accepted April 30, 2013; published OnlineFirst May 30, 2013.

References


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Denarda Dangaj, Evripidis Lanitis, Aizhi Zhao, et al.

Cancer Res  Published OnlineFirst May 30, 2013.

Updated version  Access the most recent version of this article at:
doi:10.1158/0008-5472.CAN-12-3457

Supplementary Material  Access the most recent supplemental material at:
http://cancerres.aacrjournals.org/content/suppl/2013/05/30/0008-5472.CAN-12-3457.DC1

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