Redirecting Gene-Modified T Cells toward Various Cancer Types Using Tagged Antibodies

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Abstract

**Purpose:** To develop an adaptable gene-based vector that will confer immune cell specificity to various cancer types.

**Experimental Design:** Human and mouse T cells were genetically engineered to express a chimeric antigen receptor (CAR) that binds a fluorescein isothiocyanate (FITC) molecule, termed anti-FITC CAR T cells. Various antibodies (Ab) currently in clinical use including cetuximab (Ctx), trastuzumab (Her2), and rituximab (Rtx) were conjugated with FITC and tested for their ability to bind tumor cells, activate T cells, and induce antitumor effects in vitro and in vivo.

**Results:** Anti-FITC CAR T cells recognize various cancer types when bound with FITC-labeled Abs resulting in efficient target lysis, T-cell proliferation, and cytokine/chemokine production. The treatment of immunocompromised mice with human anti-FITC CAR T cells plus FITC-labeled cetuximab (FITC-Ctx) delayed the growth of colon cancer but unexpectedly led to the outgrowth of EGFR (EGFR)-negative tumor cells. On the other hand, in a human pancreatic cancer cell line with uniform EGFR expression, anti-FITC CAR T cells plus FITC-Ctx eradicated preestablished late-stage tumors. In immunocompetent mice, anti-FITC CAR T cells exhibited potent antitumor activity against syngeneic mouse breast cancer expressing Her2 and B-cell lymphoma expressing CD20 by combining with FITC-Her2 and FITC-Rtx, respectively. In addition, the activity of anti-FITC CAR T cells could be attenuated by subsequent injections of nonspecific FITC-IgG.

**Conclusion:** These studies highlight an applicability of anti-tag CAR technology to treat patients with different types of cancers and a possibility to regulate CAR T-cell functions with competing FITC molecules.

Clin Cancer Res; 18(23); 6436–45. ©2012 AACR.

Introduction

The generation of a versatile system that affords T cells an ability to recognize various types of cancers has major clinical ramifications. One of the strategies to achieve this goal is genetic engineering to express a chimeric antigen receptor (CAR) on T cells (1–3). The extracellular domain of a CAR contains single-chain fragment variable (scFv) of VL and VH domains derived from the antigen (Ag)-binding fragment of monoclonal antibody (mAb) against cancer cells. The scFv portion is linked to a transmembrane domain followed by a tyrosine-based activation motif such as that from CD3ζ or Fce. The so-called third generation CAR includes additional activation domains from costimulatory molecules such as CD28 and CD137 (4-1BB) which serve to enhance T-cell proliferation and survival (1, 2, 4). CAR T cells seek out and destroy cancer cells by recognizing tumor-associated Ag (TAA) expressed on their surface in an MHC-independent fashion. Various preclinical and early-phase clinical trials highlight the efficacy of CAR T cells to treat patients with cancer (5–8).

Despite the promise of CAR T cells in cancer therapy, current methods encompass several limitations in its development as generalized clinical application. First, as no single TAA is expressed by more than one Ag on tumors could promote preferential growth of more aggressive, tumor Ag-negative cancer cells. Second, there also exists a major financial cost and labor-intensive procedures associated with identifying and engineering scFv against a variety of TAA. Therefore, generation of flexible CAR
Translational Relevance

While T cells capable of recognizing and destroying cancer cells expressing tumor-associated antigens show promise in treating patients, several limitations preclude the widespread use of this form of therapy. These obstacles include the fact that chimeric antigen receptor (CAR) T cells can destroy noncancerous tissue and can only recognize a single tumor-associated antigen, and labor-intensive and high financial cost associated with generating engineered T cells. We improve the existing CAR technology by developing a versatile system that grants T cells specificity to a tag conjugated with antibodies. These studies emphasize the potential of using a single-gene vector to treat patients with different types of cancers and an ability to modulate CAR T-cell responses if needed.

platforms that can confer T cells specificity against multiple TAA is highly desired.

In this report, we describe a new generation of CARs in which a single construct is unlimitedly adaptable to recognize a variety of TAAs. Our novel CAR consists of scFv derived from an anti-fluorescein isothiocyanate (FITC) mAb, which is connected with signaling motifs of CD28, 4-1BB, and CD3ζ (referred to as anti-FITC CAR). FITC is a fluochrome dye that can be cheaply and easily conjugated with Ab and safely used in human body (9, 10). Specific interaction between FITC-labeled Ab and anti-FITC CAR enables T cells to target cancers in combination with a variety of tumor-reactive mAbs, including those already applied in clinic such as cetuximab (Ctx; anti-EGFR), trastuzumab (anti-Her2; Genentech), rituximab (anti-CD20; Genentech), and control human IgG (Invitrogen) were conjugated with FITC by using a FITC-labeling kit (Thermo Scientific). An average of 3 FITC molecules were conjugated per one molecule of antibody. FITC-labeled dextran beads and phycoerythrin (PE)-labeled CD8 mAb were purchased from Sigma-Aldrich and ebioscience, respectively. Flow cytometric analysis of cell surface molecule expression was conducted by LSR-II (BD Biosciences).

Retroviral vector generation and transduction of human and mouse T cells

The retroviral vector backbone pMSGV1 was a kind gift from Dr. Richard Morgan (National Cancer Institute, Baltimore, MD) and is derived from pMSGV (16). The mouse scFv against FITC was generated according to the previous report (17) and linked to the hinge and transmembrane regions of the human CD8ε chain and the cytoplasmic regions of the human CD28, 4-1BB, and CD3ζ molecules. Transduction of human and mouse T cells was conducted as previously described (18, 19). Briefly, retroviruses were produced by transfection of anti-FITC CAR plasmid into Phoenix Eco and Ampho packaging cell lines for transduction of mouse and human T cells, respectively. Supernatants containing retroviruses were harvested 48 hours after transfection. For transduction of human T cells, 3 × 10^6 peripheral blood mononuclear cells (PBMC) were cultured in 24-well plates in the presence of OKT3 (50 ng/mL) and interleukin (IL)-2 (50 IU/mL). retroviruses were harvested 48 hours after transfection. For transduction of mouse T cells, 3 × 10^6 spleen and lymph node cells were activated with plate-bound anti-CD3 mAb (2.5 μg/mL), anti-CD28 mAb (1.2 μg/mL), and IL-2 (100 IU/mL) for 48 hours. Supernatants containing retroviruses were mixed with the activated human or mouse T cells (1 × 10^6/mL) in the presence of retronectin (10 μg/mL) and centrifuged for 2 hours at 3,000 rpm followed by incubation for 48 hours in the presence of IL-2 (100 IU/mL). The surface expression of anti-FITC CAR on transduced T cells was determined by flow cytometry after staining with FITC-Ctx or FITC-conjugated dextran beads.

Materials and Methods

Mice and cell lines

Male or female 6- to 10-week-old NOD-scid IL-2Rgamma null (NSG), DBA/2, C37BL/6, and C3H/HeN mice (Jackson Laboratory) were used for experiments under approval by the Institutional Animal Care and Use Committee. The human EGF receptor (EGFR)-positive colon cancer SW480 and Her2-positive AU565 breast cancer cell lines were obtained from American Type Culture Collection. Panc 6.03, a human pancreatic adenocarcinoma cell line expressing both EGFR and Her2, was provided by Dr. Elizabeth Jaffe (Johns Hopkins University, Baltimore, MD; ref. 11). The mouse B-cell lymphoma line 38C13 expressing human CD20 was provided by Dr. John Timmerman (University of California Los Angeles, Los Angeles, CA; ref. 12). The P815-TGL, a mouse mastocytoma cell line, was provided by Dr. Marcel R. van den Brink (Memorial Sloan-Kettering Cancer Center, New York, NY; ref. 13). P815-TGL, that stably expresses high-level human CD20 was established in our laboratory by gene transfection. Human Her2-expressing mouse mammary tumor cell lines D2F2/E2 and E0771/E2 were provided by Dr. Wei-Zen Wei (Wayne State University, Wayne, PA; ref. 14) and Dr. Qiao Li (University of Michigan, Ann Arbor, MI; ref. 15), respectively. The Phoenix Ampho and Eco packaging cell lines were purchased from Orbigen Inc.

Antigens and reagents

Cetuximab (anti-EGFR; ImClone LLC), trastuzumab (anti-Her2; Genentech), rituximab (anti-CD20; Genentech), and control human IgG (Invitrogen) were conjugated with FITC by using a FITC-labeling kit (Thermo Scientific). An average of 3 FITC molecules were conjugated per one molecule of antibody. FITC-labeled dextran beads and phycoerythrin (PE)-labeled CD8 mAb were purchased from Sigma-Aldrich and ebioscience, respectively. Flow cytometric analysis of cell surface molecule expression was conducted by LSR-II (BD Biosciences).

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T-cell culture for proliferation, cytokine production, and cytotoxicity assay

For proliferation assay, 1 × 10^5 to 3 × 10^5 anti-FITC CAR or control T cells were cultured in 96-well tissue culture
plates in the presence of FITC-labeled Abs, nonlabeled Abs, or FITC-Dex beads for 72 hours. In some experiments, anti-FITC CAR or control T cells were co-cultured with irradiated (100 Gy) SW480 cells in the presence of FITC-labeled or nonlabeled cetuximab. Proliferative activity of T cells was assessed by incorporation of 3H-thymidine during the last 16 hours of 3-day culture. Cytotoxic activity of CAR T cells against tumors was assessed by a standard 4-hour 51Cr-release assay. Radioactivity of 3H and 51Cr was measured by Wallac Microbeta TriLux counter (PerkinElmer Inc). Concentration of cytokines and chemokines produced in the culture supernatants was measured by Bio-Plex Pro system (Bio-Rad) or Milliplex kit (Millipore). All tests were conducted in triplicate wells and results are shown as mean ± SD.

In vivo models to assess antitumor therapeutic effects of CAR T cells

In prophylactic tumor models, NSG mice were injected subcutaneously in the rear flanks with 1 × 106 to 2 × 106 SW480 tumor cells and treated intraperitoneally (i.p.) with FITC-Ctx or nonlabeled Ctx (25 μg/mouse) 1 day later. One day after Ab injection, the mice were injected intravenously with 5 × 106 anti-FITC CAR T cells generated from PBMCs of healthy donors. In the therapeutic tumor model, NSG mice were injected s.c. with 1 × 106 Panc 6.03 and kept untreated until tumor grow up to approximately 500 mm3. Then, the mice were treated i.p. with FITC-Ctx or nonlabeled Ctx weekly for 3 times and injected i.v. with 5 × 106 anti-FITC CAR T cells 1 day after the first Ab injection. In mouse models using syngeneic mouse–derived tumors, C3H/HeN mice were injected i.v. with 2 × 106 human CD20–expressing 38C13 and treated i.p. with 25 μg FITC-Rtx or nonlabeled Rtx starting 4 days after tumor inoculation and repeated weekly for 3 times. Anti-FITC CAR T cells generated from T cells of syngeneic mice were transferred i.v. into the mice 1 day after the first Ab injection. In another set of experiments, C57BL/6 mice were inoculated s.c. with human Her2–positive E0771/E2 or Her2-negative E0771 tumor and kept untreated until tumor grow up to approximately 500 to 800 mm3. Thereafter, the mice were exposed to sublethal irradiation (4 Gy) and 1 day later treated i.p. with FITC-Her2 or nonlabeled Her2 (25 μg/mouse) in conjunction with i.v. transfer of 5 × 106 anti-FITC CAR T cells. Injection of Ab was repeated every 5 days for total 3 times. A cohort of mice treated with FITC-Her2 was further injected i.p. with FITC-labeled nonspecific human IgG (100 μg/mouse) every 5 days for total 4 times. In all experiments, tumor size was measured every 3 to 4 days by digital calipers in a blinded manner. The survival of the treated mice was also assessed.

Statistical analysis

The 2-tailed Student t test was used to compare 2 groups. For survival data, Kaplan–Meier survival curves were prepared, and statistical differences were analyzed using the log-rank (Mantel–Cox) test. Differences were considered to be significant at P values less than 0.05.

Results

Anti-FITC CAR T cells proliferate and kill target cells following recognition of FITC-labeled Abs

We generated a CAR construct composed of anti-FITC scFv fused with 2 costimulation signaling motifs, CD28 and CD3ζ signaling domains, designated as anti-FITC CAR (Fig. 1A). The Kd of anti-FITC scFv to fluorescein is approximately 2.3 × 10–9 mol/L (20). When human PBMCs were transduced with anti-FITC CAR retrovirus, roughly 60% of total T cells expressed anti-FITC CAR as analyzed by staining with FITC-labeled cetuximab (FITC-Ctx) or FITC-labeled dextran (FITC-Dex) beads (Fig. 1B). To confirm their functionality and specificity, anti-FITC CAR T cells were cultured in the presence of titrating doses of immobilized FITC-Ctx, Ctx, FITC-Dex beads, or soluble FITC-IgG. As a control, T cells were transduced with empty vector. Anti-FITC CAR T cells proliferated vigorously following stimulation with immobilized FITC-Ctx and FITC-Dex in a dose-dependent manner (Fig. 1C). In sharp contrast, neither immobilized Ctx nor soluble FITC-IgG induced detectable proliferation, highlighting a necessity of cross-linking the anti-FITC CAR on T cells. Control T cells did not proliferate with FITC-Ctx or FITC-Dex (Fig. 1C).

Anti-FITC CAR T cells also showed robust proliferation after co-culture with EGFR-positive SW480 colon cancer cells in the presence of FITC-Ctx (Fig. 2A). Anti-FITC CAR T cells effectively lysed FITC-Ctx–stained SW480 colon cancer cells at various effector to target ratios as compared with control T cells (Fig. 2B, left). Appreciable cytolytic activity was detected at ratios as low as 1 T cell to 20 target cells. In the presence of FITC-control IgG, cytolytic activity of anti-FITC CAR cell was comparable with that of control T cells (Fig. 2B, right). To test an ability to recognize different types of cancers when bound with different Abs, cytolytic activity of anti-FITC CAR T cells was assessed against Panc 6.03 pancreatic cancer cells, which express both EGFR and Her2, in the presence of FITC-Ctx or FITC-trastuzumab (FITC-Her2) or against Her2-positive AU565 breast cancer cells in the presence of FITC-Her2. Anti-FITC CAR T cells efficiently and specifically lysed tumors in the presence of FITC-Ctx or FITC-Her2 but showed minimal cytolytic activity with nonlabeled Ab (Fig. 2C). Anti-FITC CAR T cells lysed target tumor cells in the presence of as little as 0.01 ng/ml FITC-Her2 (10:1 effector to target), highlighting their remarkable potential to become activated by low levels of FITC-Ab bound to tumor cells (Fig. 2D). Collectively, these data show anti-FITC CAR T cells’ (i) functionality, (ii) specificity to kill tumor cells with FITC-Ab, and (iii) ability to target different FITC-tagged Abs and a diverse set of tumor cell types.

Anti-FITC CAR T cells delay tumor growth but result in the development of Ag-negative tumor

We next examined an ability of anti-FITC CAR T cells to eliminate tumors in vivo. Immunodeficient NSG mice were injected subcutaneously with SW480 colon cancer cells followed by intraperitoneal injection with Ctx, FITC-Ctx, or FITC-IgG. One day later, the mice were injected

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intravenously with anti-FITC CAR T cells. Tumor growth kinetics was similar among mice receiving anti-FITC CAR T cells plus Ctx, anti-FITC CAR T cells plus FITC-IgG, or Ctx alone (Fig. 3A, top left). Compared with these groups, the mice receiving anti-FITC CAR T cells plus FITC-Ctx significantly delayed the growth of SW480 tumor and prolonged tumor-free period and overall survival (Fig. 3A). Despite this survival advantage, however, mice treated with anti-FITC CART cells plus FITC-Ctx eventually succumbed to the tumor.

The mechanisms contributing to the failure of anti-FITC CAR T cells in long-term treatment were further investigated. CAR T cells can display a shortened life when activated with CD3 mAb plus IL-2, despite receiving prosurvival...
signals from CD28 or 41BB (2, 21). Therefore, the presence of anti-FITC CAR T cells in our model was examined in the spleen, liver, bone marrow, peripheral blood, and tumor explants. Approximately 10% of total human T cells detected in tumor explants were anti-FITC CAR T cells (Fig. 3B). Variable percentages of anti-FITC CAR T cells were found in other organs in the recipient mice, whereas it should be noted that these percentages were lower than the starting percentage of 60% at infusion. These results indicate a gradual loss of anti-FITC CAR T cells in vivo.

Eventual growth of tumor may have also resulted from intrinsic dysfunctions of anti-FITC CAR T cells, such as in vivo induction of anergy and exhaustion. To address this, T cells were enriched from the tumor explants and immediately stimulated in vitro with SW480 cells from tissue culture in the presence of FITC-Ctx or nonlabeled Ctx. T cells in the tumor explants showed significantly enhanced proliferation (Fig. 3C) and cytokine/chemokine production (Supplementary Fig. S1) by stimulation with FITC-Ctx. These results suggest that anti-FITC CAR T cells in the tumor site maintain an ability to proliferate and release soluble factors in response to FITC-Ab bound to tumor cells.

On the basis that anti-FITC CAR T cells were present in the mice and responsive to FITC stimulation, we next examined a possibility that tumor cells downregulate EGFR expression in vivo. Indeed, all tumor explants from the treated mice almost completely lost EGFR expression, as compared with SW480 cells maintained in tissue culture (Fig. 3D). It should be noted that EGFR expression on tissue culture SW480 was heterogeneous with some cells lacking EGFR. Thus, inability
of anti-FITC CAR T cells to mediate long-term regression of SW480 was probably due to preferential survival and expansion of EGFR-negative tumors, which escaped from T-cell–mediated eradication in vivo.

Anti-FITC CAR T cells mediate tumor regression of Ag-positive pancreatic tumor

Given the heterogeneity of EGFR expression on SW480 tumor cells, the therapeutic ability of anti-FITC CAR T cells was further investigated in Panc 6.03 pancreatic cancer cells which express high and homogeneous EGFR (Fig. 4A). The mice inoculated with Panc 6.03 were kept untreated until a formation of vascularized late-stage tumor at approximately 500-mm³ size and then treated with anti-FITC CAR T cells plus either FITC-Ctx or nonlabeled Ctx. Injection of anti-FITC CAR T cells and FITC-Ctx induced the complete regression of tumors and achieved long-term survival of the recipient mice (Fig. 4B). No tumor relapse occurred during the time of observation. In contrast, mice treated with anti-FITC CAR T cells and nonlabeled Ctx succumbed to the tumor. These results show the ability of anti-FITC CAR T cells to eradicate established tumors when high and homogeneous Ag is targeted.

Anti-FITC CAR T cells demonstrate therapeutic effects against syngeneic tumor in immunocompetent mice

Whereas anti-FITC CAR T cells show powerful antitumor effects on human tumors in NSG mice, these models use immunodeficient hosts and tumors allogeneic to CAR T cells. Therefore, we further evaluated the efficacy of CAR T cells against syngeneic tumors in immunocompetent hosts. Similar to human CAR T cells, anti-FITC CAR T cells generated from mouse splenic T cells showed potent functionality, as shown by a significant increase of cytokine and chemokine production by stimulation with FITC-labeled rituximab (FITC-Rtx) compared with nonlabeled rituximab (Fig. 5A). Mouse T cells expressing anti-FITC CAR devoid of intracellular signaling domains lost their ability to become activated by FITC-Ab, indicating that the signaling motifs derived from human CD28 and 4-1BB and CD3ζ are functional in mouse T cells (Supplementary Fig. S2). Among 23 types of cytokines and chemokines tested by a multiplex assay, no specific polarization pattern, such as Th1, Th2, and Th17, was observed. Anti-FITC CAR T cells generated from mouse spleen cells exhibited profound lysis of human CD20–expressing P815-TGL tumor in the presence of FITC-Rtx but not nonlabeled rituximab (Fig. 5B, left). As expected, this cytotoxic activity was not observed against CD20-negative tumor (Fig. 5B right). Anti-FITC CAR T cells which lysed CD20-expressing tumor cells in the presence of FITC-Rtx also lysed human Her2–expressing mouse mammary tumors in the presence of FITC-labeled trastuzumab (Fig. 5C). Taken together, these results indicate that anti-FITC CAR T cells have an ability to recognize and kill syngeneic tumor cells in an Ag-specific manner.

Next, the potential for anti-FITC CAR T cells to eradicate a syngeneic tumor in immunocompetent mice was examined. Mice were inoculated i.v. with human CD20–expressing 38C13 mouse tumors as a model of rituximab-insensitive B-cell lymphoma (22) and treated with a transfer of anti-FITC CAR T cells in combination with either FITC-Rtx or nonlabeled rituximab. Survival of the mice treated with FITC-Rtx was significantly prolonged compared with those with nonlabeled rituximab (Fig. 6A; P < 0.001). The therapeutic effect of anti-FITC CAR T cells was further examined in another model using E0771/E2, a mouse breast cancer line expressing human Her2. Transfer of anti-FITC CAR T cells generated from syngeneic C57Bl/6 mice and concurrent administration of FITC-Her2 induced rejection of
preestablished E0771/E2 but not Her2-negative parental E0771 tumor (Fig. 6B). These results show an ability of anti-FITC CAR T cells to mediate therapeutic effects against syngeneic tumors established in immunocompetent hosts.

The potential for CAR T cells to attack noncancerous tissues is referred to as “on-target off-tumor toxicity” and represents a major limitation of CAR T-cell therapy. Thus, it is in great demand to develop methods to terminate CAR T-cell responses to avoid the adverse effects. Because the effects of anti-FITC CAR T cells are exclusively dependent on binding with FITC-labeled Ab, we hypothesized that administration of excess amount of FITC-labeled nonspecific Ab would diminish anti-FITC CAR T-cell function by interfering with tumor cell recognition. To address this possibility, mice inoculated with E0771/E2 tumor were treated with anti-FITC CAR T cells plus FITC-Her2 and subsequently injected with FITC-labeled control IgG. While the regular CAR T-cell therapy achieved complete tumor regression, additional injections of FITC-labeled control IgG permitted eventual tumor growth (Fig. 6C). These results suggest that the in vivo effects of anti-FITC CAR T cells can be attenuated by injecting FITC-labeled nonspecific IgG probably because of competitive interference of CAR T cell–tumor interaction.
Discussion

In the current studies, we developed a novel and adaptable approach of CAR therapy in which gene-engineered T cells acquire specificity to FITC-labeled Abs and eliminate cancers by recognition of various TAAs via Ab-dependent interactions. Our results showed that anti-FITC CAR T cells undergo significant proliferation and cytokine production by stimulation with immobilized FITC and mediate tumor lysis in the presence of FITC-labeled antitumor Abs. Transfer of anti-FITC CAR T cells together with FITC-labeled antitumor Abs prevents tumor growth and induces regression of established tumors in immunodeficient mice inoculated with human tumor as well as immunocompetent mice bearing a syngeneic tumor. Importantly, injections of FITC-labeled nonspecific Ab subsequent to FITC-labeled antitumor Ab extinguish an ability of anti-FITC CAR T cells to attack target cells. Thus, our studies develop a new platform of CART-cell therapy which can recognize a variety of targets via FITC-labeled Abs while equipped with a system to attenuate its functions.

In this study, we observed that CAR T-cell therapy targeting a single TAA can result in transient antitumor effect and potentially lead to eventual outgrowth of TAA-negative variants when treating tumors expressing heterogeneous TAAs (Fig. 3). This result underscores an importance of using CAR T cells which can target more than one TAA. In conventional CAR gene therapy, preparation of multiple CAR T cells with distinct specificity is a time-consuming and labor-intensive task. With our technology, on the other hand, it is feasible to attack multiple TAAs by transferring anti-FITC CAR T cells in conjunction with multiple FITC-labeled antitumor Abs. As intratumoral heterogeneity has
been highlighted in recent studies (1), our method to target multiple TAAs could augment therapeutic effects of CAR T cells, whereas direct demonstration of such effects needs to await our further studies. For clinical translation of our method, there are still several hurdles to overcome. First, to target multiple TAAs on a single tumor cell type, mAbs against such TAAs must be available. The number and type of U.S. Food and Drug Administration–approved anti-tumor Abs are still limited at present, and our method relies on future development of clinical-grade antitumor Abs. Second, as FITC is an immunogenic molecule, injection of FITC-labeled Abs could induce anti-FITC immune responses in vivo. Indeed, we detected anti-FITC Ab in the sera of the mice treated with FITC-Rtx (Supplementary Fig. S3). Anti-FITC immunity could shorten an in vivo half-life of FITC-Abs and weaken antitumor effects of anti-FITC CAR T cells. Eventual death of the mice in our model (Fig. 6A) might be due to the emergence of anti-FITC immunity, whereas a loss of targeted Ag would be also a possible mechanism as shown in Fig. 3D. Identification of tags with a lower immunogenicity is crucial for success of our anti-tag CAR T-cell method in cancer therapy. Finally, in immunocompetent models, we used mouse tumor cells expressing human-derived Ag including CD20 and Her2, which could be highly immunogenic for mouse immune system. To rigorously assess anti-tag CAR T cells for clinical application, its antitumor effects need to be examined in fully syngeneic models, in which T cells, tumor cells, tumor Ag, and the host are all derived from MHC-matched animals.

Additional advantage of anti-FITC CAR technology is its potential to restore usefulness of mAbs attenuating growth factor receptors in patients with cancer with mutated signal transduction proteins. For example, 30% to 60% patients with colon cancer express activating Kras mutations and do not gain therapeutic benefits from treatment with cetuximab due to a loss of its effect to block EGFR signal (23, 24). Accordingly, the current American Society of Clinical Oncology guidelines recommend that patients with colorectal cancer should be screened for Kras mutations before being offered cetuximab and those with Kras mutations should not be given cetuximab treatment (25). By combining with anti-FITC CAR technology, however, cetuximab could provide therapeutic benefits even in Kras-mutated cancer, as our studies showed the antitumor effects in SW480, a colon cancer harboring a homozygous mutation in codon 12 of Kras (26). A role of FITC-labeled antitumor mAbs in our approach is to guide gene-modified T cells to target cells, and the elimination of tumor cells is mediated by the killing functions of CAR T cells. Thus, the antitumor effects of anti-FITC CAR therapy are independent of mutations in signaling proteins including Kras. While the anti-FITC CAR technology described in this study circumvents a major hurdle for individualized T-cell–based therapy, another significant challenge in CAR T-cell approach is its potential to destroy noncancerous cells expressing target Ags, so-called on-target off-tumor toxicity (27). To avoid this adverse effect, novel technologies that attenuate the effector functions of CAR T cells according to the need are in great demand. One potential approach developed by Di Stasi and colleagues is modification of CAR T cells to express an inducible caspase-9, so as to quickly eliminate them following the administration of synthetic dimerizing drug that induces caspase-9 activation (28). In our current studies, on the other hand, we highlighted that anti-FITC CAR T-cell activity can be attenuated by injecting FITC-labeled nonspecific IgG Ab. Mechanistically, excess FITC quenched the anti-FITC CAR on T cells and therefore competitively inhibited T-cell activation and effector functions. Thus, our technology might make it possible to inactivate anti-FITC T cells when adverse effects occur by ceasing the administration of FITC antitumor Ab and by injecting FITC (or FITC-labeled nonspecific Abs), while reactivating anti-tag T cells by re-injecting FITC-antitumor Ab when needed. We propose that the next generation of CARs should be equipped with improved abilities to recognize various cancer types and allow more precise on/off regulation.

In summary, we consider that our anti-tag CAR platform provides substantial advances in the CAR technology through its potential to redirect T cells to target cells via FITC-labeled antitumor Abs. It is worth highlighting that the tag used in such platform is not limited to FITC but can be applied to any types of reagents mediating protein–protein interaction and being conjugated with antitumor Abs. Indeed, during preparation of the manuscript, Urbanska and colleagues reported a method using biotin-conjugated Ab together with CAR expressing dimeric form of avidin (29). Our studies show complete tumor regression using both human tumor models in immunocompromised NSG mice and syngeneic mouse tumor models in immunocompetent hosts, emphasizing the antitumor effects mediated by this type of approach. In addition, our studies using FITC/anti-FITC scFv exemplify a possible method to avoid nonspecific interaction between avidin and endogenous biotin or biotin-like molecules in vivo. In summary, the studies serve as a proof of concept highlighting the potential use of anti-tag T cells to treat patients with different types of cancers as well as the possibility to regulate CAR T-cell functions with competing tag molecules.

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

Authors’ Contributions
Conception and design: K. Tamada, D. Geng, E. Davila
Development of methodology: D. Geng, Y. Sakoda, E. Davila
Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): K. Tamada, D. Geng, Y. Sakoda
Analysis and interpretation of data (e.g., statistical analysis, bioinformatics, computational analysis): D. Geng, E. Davila
Writing, review, and/or revision of the manuscript: K. Tamada, D. Geng, E. Davila
Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): D. Geng, N. Bansal, R. Srivastava
Study supervision: K. Tamada, E. Davila

Acknowledgments
The authors thank Dr. Scott E Strome for reviewing the manuscript, Dr. Elizabeth Jaffee (Johns Hopkins University) for providing Panc 6.03, Dr. John Timmerman for providing human CD20-expressing 38C13, Dr. Wei-
Antitumor Effect of Anti-Tag CAR T Cells

Zen Wei for providing D2F2/E2, and Dr. Koh-Hei Sonoda and Yukari Mizuno for technical supports for the experiments.

Grant Support
This study was supported by the NIH grants R01CA140917 [E. Davila] and R01HL088594 [K. Tamada] and the University of Maryland Marlene and Stewart Greenebaum Cancer Center.

References

Correction: Redirecting Gene-Modified T Cells toward Various Cancer Types Using Tagged Antibodies

In this article (Clin Cancer Res 2012;18:6436–45), which was published in the December 1, 2012, issue of Clinical Cancer Research (1), the authors regret failing to fully acknowledge the funding sources for this work.

The original text under the heading of Grant Support reads as follows:
This study is supported by the NIH grants R01CA140917 (to E. Davila) and R01HL088954 (to K. Tamada) and the University of Maryland Marlene and Stewart Greenebaum Cancer Center.

The information that should have been included is as follows:
This study is supported by NIH grants R01CA140917 (to E. Davila) and R01HL088954, by the Yamaguchi University Hospital Translational Research Fund (to K. Tamada), and by the University of Maryland Marlene and Stewart Greenebaum Cancer Center.

Reference

Published OnlineFirst January 25, 2013.
doi: 10.1158/1078-0432.CCR-13-0139
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Redirecting Gene-Modified T Cells toward Various Cancer Types Using Tagged Antibodies

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doi:10.1158/1078-0432.CCR-12-1449

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