CD27 costimulation augments the survival and antitumor activity of redirected human T cells in vivo

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The costimulatory effects of CD27 on T lymphocyte effector function and memory formation have been confined to evaluations in mouse models, in vitro human cell culture systems, and clinical observations. Here, we tested whether CD27 costimulation actively enhances human T-cell function, expansion, and survival in vitro and in vivo. Human T cells transduced to express an antigen-specific chimeric antigen receptor (CAR-T) containing an intracellular CD3 zeta (CD3ζ) chain signaling module with the CD27 costimulatory motif in tandem exerted increased antigen-stimulated effector functions in vitro, including cytokine secretion and cytotoxicity, compared with CAR-T with CD3ζ alone. After antigen stimulation in vitro, CD27-bearing CAR-T cells also proliferated, up-regulated Bcl-xL protein expression, resisted apoptosis, and underwent increased numerical expansion. The greatest impact of CD27 was noted in vivo, where transferred CAR-T cells with CD27 demonstrated heightened persistence after infusion, facilitating improved regression of human cancer in a xenogeneic allograft model. This tumor regression was similar to that achieved with CD28- or 4-1BB–costimulated CARs, and heightened persistence was similar to 4-1BB but greater than CD28. Thus, CD27 costimulation enhances expansion, effector function, and survival of human CAR-T cells in vitro and augments human T-cell persistence and antitumor activity in vivo. (Blood. 2012;119(3):696-706)

Introduction

The genetic engineering of T cells to express chimeric antigen receptors (CARs) has emerged as an attractive “off-the-shelf” approach for generating tumor antigen-specific T cells for adoptive immunotherapy. CARs couple the high-affinity binding of antibodies with the signaling domains of the TCR CD3ζ chain for antigen-specified triggering of T-cell activation similar to the endogenous TCR.1 In early phase 1/2 trials, adoptive transfer of CAR-redirected T cells (CAR-T) did not induce tumor regression because of the poor persistence of the gene-modified T cells in vivo,2,3 consistent with the finding that persistence of tumor antigen-specific T cells after adoptive transfer correlates with the regression of tumor in patients with advanced metastatic cancer.4 The addition of costimulatory domains, including the intracellular domain of CD28 and tumor necrosis factor receptor (TNFR) family members, CD134 (OX-40), inducible costimulator, and CD137 (4-1BB), into CARs can significantly augment the ability of these receptors to stimulate cytokine secretion, promote T-cell survival and enhance net antitumor efficacy in preclinical animal models of solid tumors and leukemia that lack cognate costimulatory ligands.5-12 Costimulated CAR therapy is now demonstrating promising clinical results in patients with lymphoma.13,14 CD27 (also known as TNFRSF7) is a member of the TNFR superfamily, whose expression is constitutive by human CD8 and CD4 T cells, natural killer T cells, natural killer-cell subsets, and hematopoietic progenitors and induced in FOXP3+ CD4 T-cell and B-cell subsets. Its ligand, CD70, is transiently expressed by activated T and B lymphocytes and mature dendritic cells. CD27 signaling plays a costimulatory role in T-cell activation yet appears to be dispensable for immune development because CD27−/− mice are immunocompetent, lack overt autoimmune symptoms, and respond to viral infection; however, T-cell memory responses in these mice are impaired in formation, kinetics of response, and cell number, which has been attributed to the impact of CD27 on activated T-cell survival.15,16 Similarly, T-cell priming in the absence of CD70 interaction with CD27 results in abortive clonal expansion, dysfunctional antitumor responses, and no CD8+ T-cell memory.17

The role of CD27 signaling in human T-cell activation, survival, and memory formation is less clear. In patients responding to adoptive T-cell therapy, the absolute number of CD27+ antigen-specific T cells that persist in the blood after infusion is remarkably stable,18 implying that the CD27 subset present in the early aftermath of infusion is the precursor to the emergent memory pool. Response to adoptive T-cell therapy is also associated with the transfer of high numbers of T cells expressing CD27 costimulatory receptor.19 Whether CD27 costimulatory signaling facilitates improved human T-cell survival, memory formation, and antitumor response in vivo or is a functionally dispensable marker for the evolving human T-cell memory pool is not known.

To investigate the functional role of CD27 in human T-cell memory development and antitumor function in vivo, we took advantage of the CAR approach and gene transfer technology to develop human T cells bearing a tumor antigen-specific scFv-based CAR fused with an intracellular CD3ζ signaling domain alone or in
tandem with a CD27 signaling domain. We tested whether the addition of CD27 signaling to CAR-T cells promoted antigen-induced proliferation, antiapoptosis Bcl- XL protein expression, proinflammatory cytokine production, and cytolytic functions in vitro and evaluated whether transfer of CD27-containing CAR-T cells into tumor-bearing mice resulted in improved human T-cell survival and antitumor efficacy in a xenogenic model of human cancer. We further compared CD27 with CD28 and CD137 in vivo and serve to rationalize the incorporation of CD27 costimulatory modules in the creation of antigen-specific CAR-T therapy.

Methods

CAR construction

CAR backbone constructs were generated as previously described.5 The anti-FR scFv sequence was derived from M0v19,20,21 a monoclonal antibody directed against folate receptor-α (FR). M0v19 scFv22,23 was amplified by use of the following primers: 5'-GGCGGGATCCTCTAGAGCGGC-

CD8a Hinge + TM F ata gct aac accaaccagccgagctccggttttcg

CD8a Hinge + TM R gca gtaaaggggtggagccagcgacag

CD27 ICD F gttatcaacctctagccgaaccaggaaaggaatatagct

TM F ata gct aac accaaccagccgagctccggttttcg

TM R gca gtaaaggggtggagccagcgacag

Restriction enzyme recognition sites are underlined.

CAR indicates chimeric antigen receptor; F, forward; ICD, intracellular domain; R, reverse; and TM, transmembrane.

Table 1. Primer sequences for FR-27z CAR construction

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<tr>
<th>Primer name</th>
<th>Primer sequence (5'-3')</th>
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<tr>
<td>CD8a Hinge + TM F</td>
<td>ata gct aac accaaccagccgagctccggttttcg (Nhel)</td>
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CD27 COSTIMULATED CAR T-CELL THERAPY OF CANCER

Human recombinant IL-2 (Novartis) was added every other day to a 50 IU/mL final concentration and a 0.5-1 × 10^6 cells/mL cell density was maintained. T cells were cultured for ~14 days after stimulation to a resting state as determined by decreased growth kinetics and cell size (~250 IL) via use of the Multisizer3 Coulter Counter (Beckman Coulter). Engineered cells were then adjusted to equalize the frequency of transgene expressing cells and level of surface CAR expression (mean fluorescence intensity) before functional assays.

Cell lines

Lentivirus packaging was performed in the immortalized normal fetal renal 293T cell line purchased from ATCC. Mycoplasma-free human cancer cell lines used in immune-based assays include the established ovarian cancer cell lines SKOV3, OVCAR8, OVCAR4, A1847, OVCAR3, OVCAR5, C30, and PEO-1 and breast cancer cell lines SKBR3, MCF7, MDA-231, and MDA-468. For bioluminescence assays, target cancer cell lines were transduced to express firefly luciferase (Fluc) with lentivirus and validated for positive expression by bioluminescence imaging. The mouse malignant mesothelioma cell line, AE17 (provided by Steven Albelda, University of Pennsylvania), was transduced to express FR (AE17.FR) with lentivirus. CD19-expressing K562 (CD19+K562) cells, a human erythroleukemic cell line, were provided by Michael Milone (University of Pennsylvania).

Cytokine release assays

Cytokine assays were performed by coculture of 10^6 T cells with 10^5 target cells per well in triplicate in 96-well round bottom plates in a 200-μL volume of complete media. After ~24 hours, cytokine supernatants were assayed for the presence of IFN-γ with an ELISA Kit (Biolegend). Values represent the mean of triplicate wells. IL-2, IL-4, IL-10, IFN-γ, and TNF-α cytokines were measured by flow cytometry with Cytometric Bead Array (BD Biosciences).

Cytotoxicity assays

For the cell-based bioluminescence assay, 5 × 10^5 firefly Luciferase expressing (Fluc+) tumor cells were cultured with complete media in the presence of different ratios of transduced T cells with the use of a 96-well Microplate (BD Biosciences). After incubation for ~20 hours at 37°C, each well was filled with 50 μL of DPBS resuspended with 1 μL of D-luciferin (0.015 g/mL) and imaged with the Xenogen IVIS Spectrum. Percent tumor cell viability was calculated as the mean luminescence of the experimental sample minus background divided by the mean luminescence of the input number of target cells used in the assay minus background times 100. All data are represented as a mean of triplicate wells. For extended-duration killing assays, tumor cells were labeled with carboxyfluorescein diacetate succinimidyl ester (CFSE; Molecular Probes Inc) and then cultured with T cells as described previously. FACTS analysis was performed with the use of forward and side scatter gating to determine viable cells, whereas CFSE and CD3 staining was used to distinguish T cells from unabeled tumor cells.

Flow cytometric analysis

The following mAbs were used for phenotypic analysis: allophycocyanin (APC)-Cy7 mouse anti-human CD3; FITC–anti-human CD4; APC-anti-human CD8; PE-anti-human CD45; FITC–anti-human CD45RO; PE-anti-human CD62L; PE-anti-human CD27; and FITC–anti-human CD28 (BD Biosciences). In transfer experiments, blood was obtained via retro-orbital bleeding and stained for the presence of human CD45, CD4, and CD8 T cells. Human CD45+–gated, CD4+, and CD8+ subsets were quantified with the TruCount tubes (BD Biosciences) per manufacturer’s instructions. Spleens pooled from each group were homogenized in RPMI cell culture medium. RBCs were lysed by adding 1 × FACS Lysing Solution (BD Biosciences). Cells were washed in FACS buffer (1 × PBS, 2% FCS), and 1 × 10^6 cells per sample were analyzed for transferred T cells phenotype.

Tumor cell surface expression of FR was detected by M0v18/zeL antibody (Enzo Life Sciences). CD70 (CD27 ligand) expression on SKOV3 cells was detected by FITC–anti-human CD70 antibody (BD Biosciences).
CAR expression was detected by biotin-labeled Protein L (GeneScript) at 100 ng per 10^6 cells followed by incubation with APC-conjugated streptavidin or PE-conjugated goat anti-mouse IgG F(ab')2 (Jackson Immunoresearch Laboratories). PE-conjugated antiBel-746 antibody was purchased from Southern Biotech. Isotype-matched control Abs were used in all analyses. Flow cytometric data were analyzed by FlowJo Version 7.2.5 software.

T-cell proliferation, expansion, and apoptosis

For cell division, 2 × 10^7 T cells in PBS were labeled with 2.5μM CFSE for 5 minutes at room temperature. Labeled cells were cocultured with tumor cells at 2:1 ratio in the absence of exogenous IL-2. After 5 days, cells were stained with CD3 and analyzed for CFSE dilution by FACS analyses. For expansion, viable T cells were cocultured with tumor cells at 1:1 ratio in the absence of IL-2, and T-cell counts were determined by the Multisizer 3 Coulter Counter (Beckman Coulter) and Trypan blue exclusion on day 5 and 10. For apoptosis assays, T cells were cocultured with tumor cells at 2:1 ratio in the absence of IL-2. After 3 days, T cells were detected by simultaneous staining with anti-CD3 antibody, annexin V–FITC, and 7-AAD-PerCP-Cy5.5, according to the manufacturer’s instructions (BD Pharmingen).

Xenograft model of ovarian cancer

Animals were obtained from the Stem Cell and Xenograft Core of the Abramson Cancer Center, University of Pennsylvania. Then, 8- to 12-week-old nonobese diabetic/severe combined immunodeficient/γ-chain−/− (NSG) mice were bred, treated, and maintained under pathogen-free conditions in-house under University of Pennsylvania Institutional Animal Care and Use Committee–approved protocols. Female NSG mice were inoculated subcutaneously with 3 × 10^6 SKOV3 fluc^+ cells on the flank on day 0. Five mice were randomized per group before treatment. After tumors became palpable, human primary T cells (CD4^+ and CD8^+ cells mixed at 1:1 ratio) were activated and transduced as described previously. After 2 weeks’ expansion, when tumor burden was ~250-300 mm^3, mice were injected with 10^6 CAR-T cells (~2 × 10^5 at 50% CAR^+) intratumorally or intravenously and again 5-7 days later. Tumor dimensions were measured with calipers, and tumor volumes calculated with the following formula: V = 1/2(length × width)^3, where length is greatest longitudinal diameter and width is greatest transverse diameter. Animals were imaged before T-cell transfer and approximately every 2 weeks thereafter. Tumors were resected immediately after the animals were euthanized, which was 25 days after first T-cell dose for size measurement.

Bioluminescence imaging

Imaging of tumor was performed with the Xenogen IVIS imaging system and the photons emitted from fluc^+ cells within the animal body were quantified with the Living Image Version 3.0 software (Xenogen). To summarize in brief, mice bearing SKOV3 fluc^+ tumor cells were injected intraperitoneally with D-luciferin (150 mg/kg stock, 100 μL of D-luciferin per 10 g of mouse body weight) suspended in PBS, and imaged under isoflurane anesthesia after first T-cell dose for size measurement.

Statistical analysis

The data are reported as means and SD. Statistical analysis was performed by the use of 2-way repeated-measures ANOVA for the tumor burden (tumor volume, photon counts). Student t test was used to evaluate differences in absolute numbers of transferred T cells, cytokine secretion, and specific cytotoxicity. GraphPad Prism 4.0 (GraphPad Software) was used for the statistical calculations. P < .05 was considered significant.
uniformly lower in FR-27z CAR-T cells compared with FR-z, indicating that CD27 signaling reinforces the Th-1 response. When the CD27 domain was replaced by the CD314 endodomain, which is similar in length but has no intrinsic signaling capacity,37,38 FR-314z CAR-T cells failed to increase IFN-γ secretion after coculture with FRpos SKOV3 cells, compared with FR-z (supplemental Figure 3), confirming that the costimulatory CAR effects are not because of simple extension of the intracellular domain.39 CD19-27z CAR-T cells did not produce IFN-γ, except when coincubated with CD19pos K562 cells, and untransduced T cells did not secrete cytokine when stimulated with FRpos cancer cells, illustrating the requirement for antigen specificity for CAR-T cell activity.

We next evaluated the antigen-specific cytolytic potential of FR-specific CD8+ CAR-T cells in vitro using overnight luminescence and 5-day coculture assays. CAR-T cells were cocultured with FRpos SKOV3 and A1847 cancer cells or FRneg C30 and AE17...
cells expressing firefly luciferase (FLuc$^+$) and assessed for bioluminescence after overnight culture. Representative luminescence results shown in Figure 3A reveal that both FR-z and FR-27z CAR-T cells specifically eliminated FR$^{\text{pos}}$ A1847 ovarian cancer cells but not FR$^{\text{neg}}$ C30. Untransduced or CD19-27z CAR-T cells did not lyse ovarian cancer cells, but the latter did efficiently lyse CD19$^+$ K562 cells (supplemental Figure 4). FR-z and FR-27z CAR-T cells directly and efficiently lysed FR$^{\text{pos}}$ human ovarian...
cancer cell lines SKOV3 and A1847 but not FRneg C30 or AE17 cell lines (Figure 3B). Similar to cytokine production results, FR-27z CAR-T cells demonstrated enhanced cytotoxicity, particularly at high E/T ratios, compared with FR-z CAR-T cells, but not at lower ratios \((P = .024)\). To assess the cytotoxic function of CAR-T cells in extended culture, CAR-T cells were cocultured with CFSE-labeled tumor cells for 5 days. Representative dot plots show that CFSE\(^+\) CD3-negative SKOV3 cancer cells, but not C30 cells, were eliminated when cultured with FR-specific CAR-T cells but control T cells (Figure 3C). Cocultures containing FR-specific CAR-T cells were dominated by CFSE-negative CD3\(^+\) human T cells that had eliminated all FRpos cancer cells tested (SKOV3, A1847, OVCAR4, AE17.FR) in extended culture, but not FRneg lines (Figure 3D).

**CD27 signaling improves the survival of antigen-stimulated CAR-T cells in vitro**

To determine the impact of CD27 costimulation on antigen-stimulated proliferation of redirected T cells, CFSE-labeled CAR-T cells were cocultured with FRpos SKOV3 or FRneg C30 cell lines, respectively. CFSE-labeled control CD3\(^+\) T cells did not dilute CFSE or eliminate CFSE\(^+\) CD3\(^+\) tumor cells after 72 hours’ incubation (Figure 4A). However, FR-z and FR-27z CAR-T cells both proliferated, and to a similar extent, in response to FRpos tumor stimulation measured by CFSE dilution and eliminated the tumor cell fraction, in agreement with results in the preceding paragraph (Figure 3D).

Because T-cell division does not adequately measure the extent of overall cell expansion, which encompasses both cell proliferation and apoptosis, viable cell counting was performed. In response to FRpos tumor stimulation, FR-27z CAR-T cells underwent increased numerical expansion after 10 days, compared with FR-z CAR-T cells, suggesting a survival advantage for cells receiving CD27 costimulation (Figure 4B). Nonspecific stimulation with FRneg tumor cells did not induce substantial cell expansion. CD27 signaling can induce expression of Bcl-X\(_L\),\(^{40,41}\) an antiapoptotic protein of the Bcl-2 family. When stimulated with FRpos tumor cells, more FR-27z CAR-T cells (\(\sim 20\%\) of CAR\(^+\)) expressed Bcl-X\(_L\) compared with FR-z (\(\sim 2.4\%\)) and CD19-27z CAR-T cells (\(\sim 0.9\%\); Figure 4C). Bcl-X\(_L\) up-regulation was restricted...
to the CAR\(^+\) T-cell population, confirming dependence on antigen-specific stimulation. Consistent with these findings, more viable (7-AAD\(^{-}\) annexin V\(^{-}\)) and fewer early apoptotic (7-AAD\(^{-}\) annexin V\(^{+}\)) and late apoptotic (7-AAD\(^{+}\) annexin V\(^{+}\)) T cells were detected in cocultures of FR-27z CAR-T cells and FR\(^{+}\) SKOV3 tumor cells, compared with FR-z CAR-T cell cultures where apoptosis was more prevalent (Figure 4D).

**CD27 promotes CAR-T cell survival and antitumor function in vivo**

The addition of CD28 or CD137(4-1BB) endodomains to CARs can improve CAR-T cell persistence and antitumor function in vivo.\(^{5,25,42}\) To test and compare CD27 to these domains, we generated MOv19-based FR-28z and FR-BBz CARs.\(^{25}\) Transduced human CD4\(^+\) and CD8\(^+\) T cells efficiently expressed the various
FR-specific CAR constructs (Figure 5A). CAR-T cells bearing -z, -27z, -28z, or -BBz endodomains directly and efficiently lysed FRpos SKOV3 cells in vitro but not FRneg C30 (Figure 5B). Next, immunodeficient nonobese diabetic/severe combined immunodeficient/IL-2Rγnull (NSG) mice were inoculated subcutaneously with fLuc+ FRpos SKOV3 human ovarian cancer cells on the hind flank and received intravenous injections of 10^5 CAR+ T cells on days 40 and 45 after tumor inoculation (p.i. in Figure 5C), when tumors were ~250 mm^3 in size and evident by bioluminescence imaging.

Transfer of FR-27z CAR-T cells by intravenous or intratumoral administration resulted in the rapid regression of established human tumor (Figure 5C-D and supplemental Figure 5A; P < .0001), which was superior to first-generation FR-z CAR therapy. FR-27z CAR-mediated regression was similar to that achieved with FR-28z and FR-BBz CAR-T cells. Although SKOV3 cells do express low levels of CD70, the FR-27z ligand, FR-z CAR-T cells that expressed endogenous cell surface CD27 at the time of cell infusion had only a modest impact on tumor outgrowth, compared with animals receiving untransduced T cells (P = .015), and did not express surface CD27 3 weeks after transfer (supplemental Figure 1A). Although these observations do not define the role for endogenous CD27 in this system, it does demonstrate that enforced expression of CD27 in CAR-T cells augments their antitumor function in vivo.

Significantly greater numbers of circulating human CD4+ and CD8+ T cells were observed in tumor-treated mice receiving either FR-27z or FR-BBz CAR-T cells 3 weeks after the first T-cell dose compared with FR-z and FR-28z CAR groups (Figure 5D; P < .05). Improved engraftment of FR-27z CAR-T cells required both antigen-specific stimulation and CD27 costimulation. Persistence was not a product of constitutive CD27 activity because CD19-27z CAR-T cells did not engraft or treat tumor (supplemental Figures 6-7). Furthermore, cognate antigen recognition reinvokes the persistence of CAR-T cells in vivo because mice that received FR-z CAR-T cells had increased CAR+ T-cell counts compared with mice in CD19-27z CAR-T (P = .017) or gfp T-cell groups, which had little to no detectable persistence of CAR+ T cells, respectively (supplemental Figure 6).

Notably, surface CAR expression was better maintained in the FR-28z group (Figure 5F), compared with other groups (P < .01), consistent with previous findings. As such, the absolute number of circulating CAR+ T cells in tumor-bearing mice administered FR-27z, FR-28z, and FR-BBz were not statistically different (P > .05) but greater than that observed in mice receiving first-generation FR-z CAR-T cells (supplemental Figure 5B).

Discussion

In this study, we elucidate a role for CD27 costimulatory signaling in promoting the survival of adoptively transferred human T cells in vivo and enhancing the antitumor efficacy of CAR therapy. Primary human T cells expressing a FR-specific CAR, outfitted with intracellular TCR CD3ζ and a CD27 costimulatory signaling domain in tandem, recognized and killed FR-expressing cancer cells lines in vitro and demonstrated improved antigen-dependent memory formation and antitumor potency in vivo in a mouse xenograft model of advanced cancer.

In our study, the role of CD27 costimulatory signaling in T-cell effector proliferation, activity, and survival was evaluated via incorporation of the CD27 receptor endodomain into the intracellular signaling portion of a FR-specific CAR-z construct. The addition of the CD27 signaling domain to CAR supported significant improvement in tumor antigen-specific T-cell reactivity in vitro, relative to first-generation FR-z CAR. Consistently, the production of proinflammatory cytokines such as IFN-γ by FR-27z CAR-T cells was substantially increased after coculture with all FRpos ovarian and breast cancer cell lines, compared with FR-z T cells. Interestingly, the levels of cytokine secretion measured were associated with the expression of surface FR expression by target cancer cells for both FR-27z and FR-z CAR-T cells. In overnight killing assays, provision of CD27 costimulation to CAR resulted in marginally increased cytolytic function; however, with extended coculture, both FR-27z and FR-z CARs induced complete tumor killing with no viable FR-expressing tumor cells detected. Mechanisms accounting for increased effector function by CD27 costimulated CAR-T cells in vitro are not known but appear linked in part to their ability to resist antigen-induced cell death and suggest that CAR-T cells with CD27 costimulatory capacity might demonstrate improved function and therapeutic efficacy in vivo.

With the use of in vitro assay systems, CD27 has been established as a costimulator of human T-cell responses, its importance for immune responses and memory formation in vivo has been primarily restricted to studies in which the authors use mouse model systems. Although CD27−/− mice are immuno-competent, intranasal infection with influenza virus revealed that CD27 costimulation regulates the survival and accumulation of virus-specific T cells at the site of infection independent and complementary to CD28. Moreover, T-cell memory responses are reduced in CD27−/− mice on secondary infection.

Similar results have been observed in a model of CD8+ T-cell–mediated cardiac allograft rejection where disruption of CD27–CD70 interactions contributes to reduced CD28-independent effector T-cell accumulation, function, and memory response. Alternatively, constitutive CD27 costimulatory signaling in CD70 transgenic mice promotes virus- and cancer-specific CD8+ memory T-cell formation by initially reducing effector phase contraction and supporting the maintenance of high numbers of antigen-specific T cells with increased effector function in the memory pool. Notably, superior cancer-specific CD8+ memory formation induced by constitutive CD27 ligation can protect CD70 transgenic mice against lethal tumor dose challenge in an IFN-γ-dependent manner.

The intracytoplasmic domain of CD27 used in our study and triggered naturally by CD70 ligation mediates prosurvival effects through interaction with TRAF2 and activation of Jun kinase and NF-kB, which is required for optimal effector/memory CD8+ T-cell generation. The mechanism by which CD27 prevents activation-induced cell death and promotes T-cell survival includes the up-regulation of antiapoptotic Bcl-xL protein expression and resistance to Fas-mediated apoptosis. After stimulation in vitro, increased Bcl-xL protein expression has been observed in T cells engineered to express a CD70-specific, chimeric CD27-CD3ζ CAR consisting of the both the extracellular and intracellular CD27 domains. Consistent with this finding, we observed increased expression of Bcl-xL protein in FR-27z CAR-T cells after antigen stimulation, compared with FR-z alone. Moreover, incorporation of the CD27 intracellular signaling domain to CAR also reduced T-cell apoptosis after antigen-induced activation and consequently increased numerical expansion of transduced T cells in vitro. These results suggested that provision of CD27 costimulatory signaling through CAR engagement with cognate antigen in vivo might
Figure 5. Comparison of FR-specific CARs with CD27, CD28, and 4-1BB costimulatory endodomain. (A) FR-specific CAR expression on primary human T cells. As shown, CD8^+ T cells can efficiently express FR-specific CARs with or without CD27, CD28, and 4-1BB costimulatory endodomains as measured by flow cytometry. (B) CAR-transduced T cells showed lytic function in a bioluminescent killing assay. FR CAR-T cells killed FR^+ SKOV3 but did not kill FR^- C30 cells at the indicated E/T ratio more than ~20 hours. Untransduced T cells (UNT) served as negative controls. Mean and SD of triplicate wells from 1 of at least 3 independent experiments is shown. (C) Bioluminescence images show Fluc^+ SKOV3 tumors in NSG mice immediately before and 3 weeks after first intravenous injection of 10^6 CAR-T cells on days 40 and 45 after tumor inoculation. (D) Tumors in mice treated with FR-27z, -28z, and -BBz CAR-T cells regressed; tumors treated with untransduced T cells (UNT) did not regress 3 weeks after first T-cell dose (\(P < .0001\)). Arrows indicate timing of T-cell infusion. FR-z CAR-transduced T cells only slowed tumor growth (\(P = .015\)). Before infusion, CAR^+ T-cell frequency (~50%) and surface scFv expression level (range, 315-398 mean fluorescence intensity) was equalized. (E) Circulating human CD4^+ and CD8^+ T-cell counts. In contrast to CD27, CD28 and 4-1BB signaling enhances the survival of circulating human CD4^+ and CD8^+ T cells in vivo 3 weeks after T-cell infusion (27z vs z, \(P = .029\); BBz vs z, \(P = .024\); 28z vs z, \(P = .20\)). Mean cell concentration (cells/µL) ± SD for all evaluable mice in each treatment group is shown. (F) Surface CAR expression on persisting FR-specific human CD3^+ T cells from blood of treated mice measured by flow cytometry. Mean CAR^+ expression frequency per CD3^+ T cells and SD per group is shown.
improve T-cell survival and numerical expansion, thereby significantly augmenting their potential for antitumor activity after adoptive transfer.

The role of CD27 on human T-cell activity and memory formation in vivo has not been formally evaluated to date. We first reported that after adoptive transfer of heterogeneous tumor-infiltrating lymphocytes (TILs) to patients with metastatic melanoma in vivo, a subpopulation of CD27+ tumor antigen–specific T cells was temporally selected for in vivo, suggesting that these cells possessed a function advantage in long-term survival and that CD27+ cells detectable in the blood in the early aftermath of adoptive transfer represented the precursors to the emerging memory pool. These results were later reproduced at the clonal level for HIV-specific CD8+ T cells persisting after adoptive transfer. Similarly, a population of CD27+ HIV-specific CD8+ T cells with memory characteristics and direct effector capabilities has been observed in vivo when viral replication is inhibited with antiretroviral therapy. Consistent with these results, retrospective analysis of TILs administered to patients with melanoma revealed a significant association between the absolute number of administered CD27+ CD8+ TILs and the ability of those TILs to persist in vivo and mediate objective clinical response after transfer. Because T-cell persistence after infusion is a major factor limiting adoptive cell therapy, the elucidation of approaches to promote T-cell survival has the potential to significantly improve response rates in adoptive immunotherapy.

The impact of CD27 costimulation on human T-cell survival and antitumor activity was most evident in vivo, where CD27-bearing CAR-T cells facilitated superior regression of established tumors in a human ovarian cancer xenograft model compared with the marginal inhibition achieved with conventional, noncostimulated CAR-T cells. Consistent with clinical observations, tumor regression in our model was associated with enhanced T-cell persistence in vivo. Tumor regression and T-cell persistence were antigen-specific because transfer of CD19-27z T cells had no impact on tumor progression and resulted in poor persistence after intratumoral infusion. Moreover, tumor regression and T-cell persistence was increased in mice that received first-generation FR-z CAR-T cells, compared with costimulated CD19-27z CAR, demonstrating that provision of a CD27 costimulatory domain in the absence of antigen-specific ligation of the CAR does not substantially bolster T-cell survival and effector function in vivo. In this line, the greatest number of CAR+ T cells persisting in the blood 1 month after the first T-cell dose was observed in those animals administered FR-27z CAR-T cells followed by FR-z and then CD19-27z, indicating that simultaneous TCR CD3ζ signaling and CD27 costimulation triggered by CAR ligation with antigen improves on TCR signaling alone, implicating a role for CD27 costimulation in memory T-cell formation in vivo.

Our results support the notion that human T cells that are enabled to receive CD27 costimulatory signals in conjunction with CD3ζ signaling receive amplified antiapoptotic signals that facilitate enhanced effector activity and better survival in vivo, assuring the generation of stable human T-cell memory. The addition of costimulatory domains, particularly the intracellular domains of CD28, and the tumor necrosis factor receptor family members, CD134 and 4-1BB (CD137), can also significantly augment the ability of these receptors to stimulate cytokine secretion, support T-cell survival and enhance antitumor efficacy in preclinical animal models using both solid tumors and leukemia that lack the expression of their cognate costimulatory ligands.

Results of comparative in vivo studies of CARs containing these various costimulatory domains demonstrated that CD137 (4-1BB), like CD27, another member of the TNFR superfamily enhances T cell antitumor activity and persistence. In contrast, CD28, which can support enhanced antitumor activity, does not support robust numerical T-cell persistence. Rather, CD28 supports stable surface CAR expression, which may be attributed in part to the inclusion of its transmembrane region in the CAR construct, as suggested previously. Notably, each of these costimulatory molecules can dramatically improve the activity and overcome the limitations of first-generation CAR approaches by improving the persistence of transferred T cells in vivo. These results rationalize the clinical investigation of CD27 costimulated CAR-T cell therapy in combination with lymphodepleting pre-conditioning for the treatment of cancer. Our data further suggest that the combination of CD27 or CD137 endodomains with the CD28 signaling domain may be more effective than CD27, CD137 or CD28 alone.

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Authorship

Contribution: D.-G.S., Q.Y., M.P., and G.M.H. performed research; M.F. provided vital new reagents; D.-G.S. collected data and performed statistical analysis; D.J.P. designed research and interpreted data; and D.S. and D.J.P. wrote the manuscript.

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