Introduction

Chimeric antigen receptors (CARs) most commonly combine the antigen-recognizing portion of a mAb with the signaling machinery of T cells. When these molecules are genetically grafted into T lymphocytes, they allow these cells to bind to tumor surface antigens in an MHC-independent fashion and promote T cell costimulation, thereby activating their cytotoxic pathways against the malignant cells (1). Autologous T cells expressing CD19-directed CARs (CD19.CARTs) have shown remarkable activity in patients with acute lymphoblastic leukemia (ALL) (2–6) and some activity in patients with chronic lymphocytic leukemia or small lymphocytic lymphoma (CLL/SLL) (7–9) or non-Hodgkin lymphoma (NHL) (10–13). Nonetheless, sustained clinical responses due to CD19.CARTs usually require long-term persistence and invariably are associated with B cell aplasia; CD19 is a pan–B cell marker, and normal B lymphocytes might be spared to avoid profound hypogammaglobulinemia. We therefore took advantage of the surface expression of Igs on mature B lymphocytes and mature B lymphoid malignancies, since each cell expresses either κ or λ light chains, but not both. We reasoned that targeting the light chain subtype expressed by monoclonal malignant NHL and CLL/SLL B cells should efficiently kill tumor cells, while sparing normal B cells expressing the reciprocal subtype. This concept is also potentially applicable to multiple myeloma (MM). Although plasma cells no longer express surface Igs, several groups have described an MM-initiating population that expresses surface Igs (14). We have previously devel-

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Conflict of Interest: While this clinical trial was being conducted, the Center for Cell and Gene Therapy at BCM had a Collaborative Research Agreement with Celgene Corporation and Bluebird Bio.

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infusion nor had absolute lymphocyte counts (ALCs) above 500/μL received 12.5 mg/kg cyclophosphamide (CTX) 4 days before the first infusion of κ.CARTs. Five patients received 1 final cycle of chemotherapy within 4 weeks of κ.CART infusion, as documented in Tables 1 and 2. These chemotherapeutic regimens had been previously chosen by the referring physicians as salvage treatment and were not specifically selected for their lymphodepleting potential.

** Characteristics of infused CARTs.** We manufactured 27 κ.CART lines from peripheral blood mononuclear cells (PBMCs) isolated from 24 patients (Figure 1). One patient had 2 cell lines and another patient had 3 cell lines made to allow repeat infusions. CAR transduction levels were adequate (>80%) in all manufactured T cell products, regardless of the cytokine(s) used for the expansion (Supplemental Figure 1B; supplemental material available online with this article; doi:10.1172/JCI86000DS1). All lines were composed of more than 99% CD3+ T cells, and each contained a variable ratio of CD4+ and CD8+ cells, with an overall CD8 predominance in the T cell products expanded in IL-2 (78% ± 11%) compared with those expanded in IL-7 and IL-15 (56% ± 12%; \( P < 0.001 \)) (see Methods and Supplemental Figure 1C). The majority of κ.CARTs were CD45RO+ and lacked CCR7, but a small fraction expressed the central memory–associated phenotypic markers CD62L, CD27, and CD28 (Supplemental Table 1). T cell products grown with IL-7 and IL-15 had approximately twice as many CD45RA+ cells as those grown in IL-2 (4.9% ± 4.1% vs. 10.7% ± 7.1%, \( P = 0.03 \)) (Supplemental Table 1). NK cells (CD3–CD56+) were not detectable. All products demonstrated cytotoxicity against κ+ targets in vitro, as assessed by 51Cr-release assays (Supplemental Figure 1D). Cytotoxic activity against κ– targets was negligible. Eight patients did not receive their cell lines (Figure 1), because they pursued alternative treatment outside our institution (6 patients), had progressive disease (PD) during cell manufacture (1 patient), or had no evidence of disease at the time of planned infusion (1 patient).

** κ.CART expansion and persistence.** Molecular signals for κ.CARTs were consistently detected in the peripheral blood at low levels 3 hours after the first κ.CART infusion but increased to peak at 1 to 2 weeks after the first infusion (94 ± 186 copies/μg of PBMC DNA and 248 ± 750 copies/μg of DNA at weeks 1 and 2, respectively, for all patients). The signals then declined to lower levels by week 6 (26 ± 49 copies/μg of DNA) (Figure 2). Seven patients received a second infusion. The difference in expansion between the first and second infusions was not statistically significant (AUCs for 2 and 6 weeks after infusion: \( P = 0.109 \) and \( P = 0.219 \), Wilcoxon signed-rank test). Transgene levels were always below the threshold needed to detect a distinct CART population by flow cytometry and became almost undetectable 6 months after the last infusion (3 ± 4 copies/μg of PBMC DNA). There was no correlation between transgene levels in the peripheral blood and preinfusion ALC, disease type, cell dose, cytokines used in culture (IL-2 vs. IL-7 and IL-15), or clinical response (data not shown).
Acute and long-term toxicities. All infusions were well tolerated. Apart from a patient with MM who had a grade 3 lymphopenia that was deemed possibly related, none of the adverse events reported (most frequently anemia, leukopenia, fatigue, hyper- or hypokalemia, and elevated aspartate aminotransferase [AST]) were considered to be related to κ.CART infusion. The vast majority of patients had baseline B cell lymphopenia and polyclonal hypogammaglobulinemia as a result of prior treatment, the biology of their underlying disease, or both. With the exception of the 2 CLL patients, B cell lymphopenia was especially pronounced in the NHL patient group (with 1.5% ± 2% of CD19+ cells gated on CD45+ lymphocytes at the time of infusion). This made assessment of new-onset B lymphopenia due to κ.CARTs challenging.

Table 1. Characteristics of patients with NHL or CLL

<table>
<thead>
<tr>
<th>UPIN</th>
<th>Age</th>
<th>Sex</th>
<th>Diagnosis</th>
<th>Previous therapies</th>
<th>Cytokines in CART culture</th>
<th>Time from last chemo. treatment</th>
<th>Pre-CART CTX</th>
<th>DL</th>
<th>CAR+ cells in product (%)</th>
<th>CAR+ T cells/m² admin.</th>
<th>No. of infusions</th>
<th>Best response</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>53</td>
<td>F</td>
<td>LPL</td>
<td>R-COMP, 2CDA, BEAM/ASCT, dexamethasone/bortezomib</td>
<td>IL-2</td>
<td>9 wk</td>
<td>Yes</td>
<td>2</td>
<td>87</td>
<td>1.7 × 10⁵</td>
<td>1</td>
<td>NR</td>
</tr>
<tr>
<td>2</td>
<td>59</td>
<td>M</td>
<td>FL/DLBCL</td>
<td>R-COMP/XRT, FCR, R-ICE, TTR, CD19.CART, R-bendamustine</td>
<td>IL-2</td>
<td>4 wk</td>
<td>No</td>
<td>1</td>
<td>85</td>
<td>1.7 × 10⁵</td>
<td>3</td>
<td>CR × 32+ mo</td>
</tr>
<tr>
<td>3</td>
<td>70</td>
<td>M</td>
<td>DLBCL</td>
<td>R-COMP, BEAM/ASCT, bortezomib</td>
<td>IL-2</td>
<td>6 d</td>
<td>No</td>
<td>2</td>
<td>90</td>
<td>9.0 × 10⁷</td>
<td>1</td>
<td>NR</td>
</tr>
<tr>
<td>4</td>
<td>72</td>
<td>M</td>
<td>CLL/SLL</td>
<td>R-bendamustine</td>
<td>IL-2</td>
<td>4 wk</td>
<td>No</td>
<td>2</td>
<td>91</td>
<td>9.1 × 10⁴</td>
<td>1</td>
<td>NR</td>
</tr>
<tr>
<td>5</td>
<td>55</td>
<td>M</td>
<td>LPL</td>
<td>R-EXP, R-COMP, R-bortezomib</td>
<td>IL-2</td>
<td>1 yr</td>
<td>No</td>
<td>3</td>
<td>94</td>
<td>1.9 × 10⁴</td>
<td>2</td>
<td>PR × 3 mo</td>
</tr>
<tr>
<td>6</td>
<td>59</td>
<td>M</td>
<td>DLBCL</td>
<td>R-COMP, R-ICE, R-BEAM/ASCT, dexamethasone</td>
<td>IL-7/IL-15</td>
<td>16 wk</td>
<td>No</td>
<td>3</td>
<td>85</td>
<td>1.7 × 10⁴</td>
<td>6</td>
<td>CR × 6 wk</td>
</tr>
<tr>
<td>7</td>
<td>69</td>
<td>F</td>
<td>CLL/SLL</td>
<td>R-fludarabine, R-bendamustine</td>
<td>IL-7/IL-15</td>
<td>1 yr</td>
<td>No</td>
<td>3</td>
<td>86</td>
<td>1.6 × 10⁴</td>
<td>2</td>
<td>SD × 6 wk</td>
</tr>
<tr>
<td>8</td>
<td>75</td>
<td>M</td>
<td>MCL</td>
<td>R-hCVAD, bortezomib, carfilzomb, lenalidomide, R-bendamustine</td>
<td>IL-7/IL-15</td>
<td>20 d</td>
<td>No</td>
<td>3</td>
<td>86</td>
<td>1.8 × 10⁴</td>
<td>1</td>
<td>NR</td>
</tr>
</tbody>
</table>

Table 2. Characteristics of patients with MM

<table>
<thead>
<tr>
<th>UPIN</th>
<th>Age</th>
<th>Sex</th>
<th>Myeloma subtype</th>
<th>Previous therapies</th>
<th>Cytokines in CART culture</th>
<th>Time from last chemo. treatment</th>
<th>Pre-CART CTX</th>
<th>DL</th>
<th>CAR+ cells in product (%)</th>
<th>CAR+ T cells/m² admin.</th>
<th>No. of infusions</th>
<th>Best response</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>56</td>
<td>M</td>
<td>IgGκ</td>
<td>RVD, melphalan/ASCT</td>
<td>IL-2</td>
<td>34 wk</td>
<td>Yes</td>
<td>2</td>
<td>92</td>
<td>9.2 × 10⁷</td>
<td>1</td>
<td>SD × 17 mo</td>
</tr>
<tr>
<td>7</td>
<td>53</td>
<td>F</td>
<td>IgGκ</td>
<td>RD, VD, RVD, CyBorD, Melphalan/ASCT</td>
<td>IL-2</td>
<td>27 wk</td>
<td>Yes</td>
<td>3</td>
<td>76</td>
<td>1.5 × 10⁴</td>
<td>2</td>
<td>SD × 24 mo</td>
</tr>
<tr>
<td>8</td>
<td>58</td>
<td>F</td>
<td>κ</td>
<td>VAD, melphalan/ASCT, XRT</td>
<td>IL-2</td>
<td>2.5 yr</td>
<td>Yes</td>
<td>3</td>
<td>92</td>
<td>1.8 × 10⁴</td>
<td>1</td>
<td>SD × 6 wk</td>
</tr>
<tr>
<td>11</td>
<td>54</td>
<td>M</td>
<td>κ</td>
<td>VD, RVD, melphalan/ASCT, VDT-PACE, VDT-AC</td>
<td>IL-7/IL-15</td>
<td>5 d</td>
<td>No</td>
<td>3</td>
<td>91</td>
<td>1.8 × 10⁴</td>
<td>1</td>
<td>NR</td>
</tr>
<tr>
<td>12</td>
<td>60</td>
<td>M</td>
<td>Igκx</td>
<td>RD, VD, VAD, VDT-PACE, pomalidomide, LGH447</td>
<td>IL-7/IL-15</td>
<td>4 wk</td>
<td>No</td>
<td>3</td>
<td>91</td>
<td>1.8 × 10⁴</td>
<td>1</td>
<td>NR</td>
</tr>
<tr>
<td>14</td>
<td>69</td>
<td>F</td>
<td>IgGC</td>
<td>VTD, melphalan/ASCT + thalidomide, DT, CyBorD, bendamustine, carfilzomib, carfilzomb / lenalidomide, CTX</td>
<td>IL-7/IL-15</td>
<td>15 wk</td>
<td>Yes</td>
<td>3</td>
<td>90</td>
<td>1.9 × 10⁴</td>
<td>2</td>
<td>SD × 6 wk</td>
</tr>
<tr>
<td>16</td>
<td>43</td>
<td>F</td>
<td>IgGC</td>
<td>RVD, melphalan/ASCT + lenalidomide, RD, RVD, CTX, pomalidomide/ASCT, CTX/pomalidomide/dexamethasone, bortezomib</td>
<td>IL-7/IL-15</td>
<td>19 d</td>
<td>No</td>
<td>3</td>
<td>93</td>
<td>1.9 × 10⁴</td>
<td>1</td>
<td>NR</td>
</tr>
<tr>
<td>8B</td>
<td>59</td>
<td>F</td>
<td>κ</td>
<td>VAD, melphalan/ASCT, XRT, κ.CART, melphalan/ASCT</td>
<td>IL-7/IL-15</td>
<td>28 wk</td>
<td>Yes</td>
<td>3</td>
<td>94</td>
<td>1.8 × 10⁵</td>
<td>2</td>
<td>SD × 6 wk</td>
</tr>
</tbody>
</table>

4Low-dose CTX (12.5 mg/kg). B This patient was re-enrolled in the trial. (R)(V)D, (lenalidomide), (bortezomib), dexamethasone; CyBorD, cyclophosphamide, bortezomib, dexamethasone; VAD, bortezomib, doxurubicin, dexamethasone; (V)DT, (bortezomib), dexamethasone, thalidomide; PACE, cisplatin, doxorubicin, cyclophosphamide, and etoposide; AC, doxorubicin, cyclophosphamide.
gating on CD4 + cells (17.3% ± 7.9%) compared with that detected
before being enrolled in the current study and were no lon-
ger detectable by PCR analysis of peripheral blood. While await-
ing k CAR manufacture, the patient received 1 dose of bendamustine
because of active disease. Four weeks later, he had evidence
of residual disease in the neck by PET/CT scan. He received one
k CART infusion, followed by a second infusion 8 weeks later,
without intervening chemotherapy. The patient entered a CR
after the second infusion, and this response has been sustained
for almost 3 years (Figure 4). Patient 9 had progressive improve-
ment of pelvic lymphadenopathy and achieved a CR after the
third infusion of k CARTs (Figure 5). Seven weeks later, however,
he had recurrence of disease (in the axillary lymph node) despite
a fourth infusion. His disease has, however, remained with minimal
progression for more than 1 year. Patient 6 (lymphoplasmacytic
lymphoma [LPL]) and patient 11 (CLL) had transient PR and SD,
respectively. The remaining 5 of 9 NHL or CLL patients (includ-
ing the 3 who had received a final cycle of chemotherapy within 4
weeks of k CART infusion) had PD.

Four of seven MM patients had responses. Patients 4 and
7 had prolonged SD for 17 and 24 months. Patient 4 had only
minimal residual disease (MRD) after high-dose melphalan and
autologous stem cell transplantation (ASCT) (positive immu-
nofixation with unmeasurable monoclonal protein) and main-
tained stable MRD for 17 months after a single k CART infusion.
Patient 7 had a progressive decline in her paraprotein levels
(2,240 to 1,730 mg/dl IgG) and improvement in anemia (11.6
to 14.4 g/dl hemoglobin), which was sustained for 2 years (Fig-
ure 6). Neither of these 2 patients was on lenalidomide (or any
other immunomodulatory drugs) at the time of k CART infusion,
either because they had previously progressed on the drug or
were intolerant of it. Two other patients (nos. 8 and 14) met the
criteria for transient SD, namely a less than 50% reduction and
a less than 25% increase in paraprotein levels (38% free k light
chain reduction in patient 8 and 11% increase in IgGk in patient
14). Patient 8 was re-treated with k CARTs 1.5 years later, after
receiving additional conventional therapy, again with transient
SD. Three of seven patients, including the two who had received
a final cycle of chemotherapy within 4 weeks of k CART infusion,
had no response to k CARTs.

We investigated whether the patients’ responses correlated
with numbers of k CARTs infused, blood cell counts at infusion
(total white blood cell, absolute lymphocyte, and absolute neu-
rophil counts), circulating Ig and k light chain levels, and plasma
cytokine levels. We found no significant association between
these parameters and response.

We further analyzed the antitumor immune responses in the
recipients to seek evidence for newly emergent immunity to addi-
tional tumor-associated antigens. No evidence for such “epitope
spreading” was obtained, as we found no differences in the fre-
with diffuse large B cell lymphoma (DLBCL), the rates of CRs to CD19.CARTs correlate with the intensity of the preconditioning chemotherapy before CD19.CART infusion, ranging from 12.5% (17) to 57% (12), according to the doses of the lymphodepleting drugs fludarabine and CTX. Our patients received no or limited lymphodepleting chemotherapy (12.5 mg/kg CTX) that produced a maximum 30% reduction in lymphocyte counts: indeed, the 2 patients who had a CR received no pretreatment lymphodepletion. More profound lymphodepletion immediately before κ.CART infusion, by depleting Tregs, downregulating immunoinhibitory pathways such indoleamine 2,3-dioxygenase (IDO) (18) in the tumor environment, and creating a favorable homeostatic cytokine milieu for T cell expansion, will likely increase the therapeutic activity of κ.CARTs.

Our clinical study also enrolled patients with MM. There are few reported clinical data for MM patients treated with CARTs. A recent report from China describes the outcomes of 5 MM patients treated with CD138.CARTs, 4 of whom achieved up to 7 months of SD (19). We observed modest antimyeloma effects, documented by a reduction of the paraprotein, a selective reduction of free κ light chains, and an improvement of anemia. These effects were sustained for up to 24 months.

Figure 3. Biological effects observed after κ.CART infusion. After κ.CART infusion, a transient decline in total B cell numbers and in the κ/λ ratio in MM patients (n = 8, paired Student’s t test) was observed (A). In general, there was a decrease in the mean fluorescence intensity of κ light chain expression during the first 2 weeks after κ.CART infusion; data from 1 representative patient are shown in B, with κ.CART expansion data in the top panel and κ light chain expression data in the bottom panels. Numbers in the dot plots correspond to the percentage of CD19+ (upper left quadrant) and CD3+ (lower right quadrant) PBMCs; histogram shows the distribution of the intensity of surface κ light chain staining in CD19+ PBMCs, highlighting the κ (left peak) and κ’ (right peak) population, at each of the time points depicted. Inflammatory cytokine levels (shown for IL-6) increased modestly after κ.CART infusion (C), in both NHL (n = 17 infusions) and MM (n = 10 infusions) patients (paired Student’s t test), and no clinical evidence of CRS was observed. There was no significant generation of HAMAs after κ.CART infusion (D).

Discussion
We report the first clinical trial to our knowledge involving the treatment of B cell–derived malignancies with CARTs targeting a clonally restricted B cell marker intended to limit B cell aplasia while maintaining antitumor activity. We found that adoptive transfer of CARTs that target the κ light chain of Igs is feasible and safe at all dose levels studied and that the κ light chain is a validated target for NHL, since κ.CARTs can induce clinical responses, including sustained CRs, in patients with NHL.

The US Food and Drug Administration (FDA) has granted the “breakthrough” designation to CD19.CARTs for the treatment of refractory or relapsed ALL on the basis of the high rate of clinical responses achieved in different clinical studies (3, 5, 6). In contrast, the efficacy of CD19.CARTs in patients with refractory or relapsed CLL or SLL and other NHLs appears less striking. For example, the overall response rate in a study of CD19.CART treatment of CLL is currently 57% (16), while in patients with diffuse large B cell lymphoma (DLBCL), the rates of CRs to CD19.CARTs correlate with the intensity of the preconditioning chemotherapy before CD19.CART infusion, ranging from 12.5% (17) to 57% (12), according to the doses of the lymphodepleting drugs fludarabine and CTX. Our patients received no or limited lymphodepleting chemotherapy (12.5 mg/kg CTX) that produced a maximum 30% reduction in lymphocyte counts: indeed, the 2 patients who had a CR received no pretreatment lymphodepletion. More profound lymphodepletion immediately before κ.CART infusion, by depleting Tregs, downregulating immunoinhibitory pathways such indoleamine 2,3-dioxygenase (IDO) (18) in the tumor environment, and creating a favorable homeostatic cytokine milieu for T cell expansion, will likely increase the therapeutic activity of κ.CARTs.

Our clinical study also enrolled patients with MM. There are few reported clinical data for MM patients treated with CARTs. A recent report from China describes the outcomes of 5 MM patients treated with CD138.CARTs, 4 of whom achieved up to 7 months of SD (19). We observed modest antimyeloma effects, documented by a reduction of the paraprotein, a selective reduction of free κ light chains, and an improvement of anemia. These effects were sustained for up to 24 months.
In preclinical studies, we did not observe deleterious effects of physiological levels of soluble Ig on the function of κ.CARTs. Indeed, soluble Ig did not impair the capacity of κ.CARTs to eliminate κ-tumor cells and appeared to sustain the expansion of κ.CARTs, which may partially explain the observed clinical responses to κ.CARTs in patients with NHL. However, we also cannot exclude the possibility that higher levels of free κ-light chains, such as those seen in κ-restricted MM, cause adverse effects on κ.CARTs, either by blocking the recognition of κ-light chains on the surface of targeted cancer cells or by causing excessive T-cell stimulation and exhaustion, thus limiting the therapeutic effect. On the other hand, plasma cells, including malignant counterparts, have minimal (if any) surface expression of light chains, and that can explain, to some extent, why the clinical responses were less striking in patients with MM. It would have been interesting to measure the distribution and persistence of infused κ.CARTs in the bone marrow of patients with MM, but the IRB-approved protocol did not mandate bone marrow studies as long as there was measurable disease by paraproteinemia, which was present in all of these patients.

How can we improve upon these outcomes? Clinical data in patients with ALL infused with CD19.CARTs suggest that the nature of the costimulation provided within the CD19.CAR may affect CART in vivo persistence. Indeed, while CD28 and 4-1BB costimulation of CD19.CARTs are equally effective in inducing clinical responses in patients with relapsed ALL, 4-1BB costimulation may ensure a longer persistence of CARTs and potentially more durable remissions. In addition, early in vitro studies and more recent animal experiments suggest that CARs that include long spacers derived from the constant regions of human Ig may...
We conducted a phase 1 study (ClinicalTrials.gov NCT00881920) designed to assess the feasibility and safety of infusing escalating doses of autologous, polyclonally activated peripheral blood T cells that were genetically modified to express a light chain–specific CAR (\(\kappa\).CART) in patients with relapsed or refractory \(\kappa\)‑restricted lymphoproliferative disorders (NHL, CLL, and MM). All patients had to have measurable disease at the time of infusion (Fig -1). Patients with CLL or an ALC above 500/\(\mu\)l and who had not received any chemotherapy within the previous 4 weeks were given low-dose (12.5 mg/kg) CTX as a single infusion 4 days before administration of the first dose of \(\kappa\).CARTs. Patients on chemotherapy at the time of treatment could receive \(\kappa\).CARTs no sooner than 4 days after finishing their last cycle of chemotherapy. Otherwise, no chemotherapy was given to patients before or after \(\kappa\).CART infusion. We administered 3 dose levels of \(\kappa\).CARTs: 2 \(\times\) 10^7 (dose level 1); 1 \(\times\) 10^8 (dose level 2); and 2 \(\times\) 10^8 (dose level 3) cells/m². These doses were based on total cell numbers, regardless of the percentage of CAR⁺ cells. We used an identical dose of \(\kappa\).CARTs for all patients at each dose level before escalation. Additional infusions of the same dose of \(\kappa\).CARTs were allowed as long as there was evidence of clinical benefit, defined as at least SD.

Additional infusions were administered at least 6 weeks apart, and no chemotherapy was given before \(\kappa\).CART infusion. Clinical and laboratory evaluations were performed at weeks 1, 2, 4, and 6 and months 3, 6, 9, and 12 after CART infusion, and yearly thereafter. Adverse events during and after T cell infusions were graded according to the NIH Common Terminology Criteria for Adverse Events (CTCAE), version 4 (http://ctep.cancer.gov). Responses were assessed by imaging or laboratory studies, as applicable, at week 6 after CART infusion and were defined as CR, PR, SD, or PD, according to the NCI’s Response Evaluation Criteria in Solid Tumors (RECIST) (23), with modifications based on the International Working Group criteria for NHL (24); the National Cancer Institute Working Group for CLL (25); or the modified (International Myeloma Working Group [IMWG]) uniform response criteria for MM (26).

Generation of retroviral constructs. We cloned the Ab targeting the \(\kappa\) light chain of human Ig produced by the CRL-1758 mouse hybridoma (ATCC) as a single chain (scFv) and generated a second-generation CAR construct containing both CD28 and \(\zeta\) endodomains (15). A spacer region derived from the human IgG1-CH2CH3 domains was cloned in-frame between the scFv and the signaling domains to facilitate detection by phenotypic analysis of the transgenic product. This cassette was then cloned into the SFG retroviral backbone. We generated the clinical-grade packaging cell line using PG13 cells (gibbon ape leukemia virus pseudotyping packaging cell line; CRL-10686; ATCC) (27). We used the highest-tier clone to establish a master cell bank and released the clone for clinical use only after safety testing and vector sequencing. We stored the final viral supernatant at ~80°C and tested it before clinical release.

Generation and transduction of \(\kappa\).CARTs. To generate \(\kappa\).CARTs, we transduced PBMCs obtained by Ficoll density centrifugation of peripheral blood obtained by phlebotomy 1–3 months before CART administration. We activated PBMCs with OKT3 Ab (Janssen Biotech) or CD3 and CD28 Abs (Miltenyi Biotec) and recombinant human IL-2 (IL-2, 100 U/ml; Prometheus) or IL-7 (10 ng/ml; R&D Systems) and IL-15 (5 ng/ml; R&D Systems) in 24-well plates precoated with a recombinant fibronectin fragment (FN CH-296, Retronectin Takara; Clontech). After transduction, T cells were expanded ex vivo in the presence of recombinant human IL-2 (ril-2) (100 U/ml) or IL-7 (10 ng/ml) and IL-15 (5 ng/ml), added twice a week. A change to the process of manufacture took place during the trial, when IL-7 and IL-15 replaced IL-2 because of our own and others’ observation that the combination of IL-7 and IL-15 better preserves the CD8⁺CD45RA⁻CCR7⁺ subset in culture, which is associated with superior expansion and persistence of CARTs in vivo (28). The characteristics of the T cell products are summarized in Supplemental Figure 1 and Supplemental Table 1. The generation of \(\kappa\).CARTs required a median of 17 days (range 10–27) of culture in the 14 T cell products generated using IL-2 and IL-15 (range 12–17 days) in the 13 T cell products expanded in the presence of IL-7 and IL-15. The expansion of T cells grown in IL-7 and IL-15 was overall better than that of T cells grown in IL-2 (Supplemental Figure 1A).

Immunophenotyping. We used phycoerythrin (PE), FITC, peridinin chlorophyll protein (PerCP) or allophycocyanin-conjugated (APC-conjugated) CD3 (clone SK7); CD4 (SK4); CD8 (SK1); CD56 (B159); CD19 (SJ25C1); TCR-\(\zeta\) (HI100); CCR2 (4B607); CCR4 (1G1); CCR5 (2D7/CCR5); CCR7 (3D12); CXCR3 (IC6/CXCR3); CXCR4 (12G5); CD162 (KPL-1); and CD54 (HA58);
CD38 (HB7); CD106 (51-10C9); CD11a (HI11); CD11c (B-ly6); CD18 (6.7); and χ (TB28-2) and λ (1-155-2) light chain Abs (all from BD Pharmingen) to stain the T cell products or tumor cells. We included control samples labeled with the appropriate isotype-matched Abs in each experiment. The κ.CAR was detected with an Fc-specific Alexa Fluor 647-conjugated goat polyclonal F(ab)2 fragment anti-human IgG (catalog 109-606-088; Jackson ImmunoResearch), which recognizes the IgG1-CH2CH3 component of the CAR. Cells were analyzed by a FACScan (BD) equipped with a filter set for 4 fluorescence signals, using CellQuest software. Data analysis was performed using FlowJo Software (Tree Star). In selected experiments, frozen PBMCs from pre- and post-CART infusion time points were thawed and the number of CD19+ cells and of κ+ cells enumerated by FACS using CountBright beads (Invitrogen).

Cytotoxicity assays. The cytotoxic specificity of each T cell line was measured in a standard 4-hour 51Cr release assay using effector-to-target (E:T) ratios of 40:1, 20:1, 10:1, and 5:1. Daudi (κ+ tumor cells), HDLM-2 (κ+ tumor cells), and K562 (NK-sensitive cells) were used as target cells. The target cells were labeled simultaneously for 1 hour with 51Cr. We calculated the percentage of specific lysis as follows: [(experimental release – spontaneous release)/(maximum release – spontaneous release)] × 100.

Real-time quantitative PCR of the κ.CAR transgene. We quantified the integrated genome of the retrovirus encoding the κ.CAR by real-time quantitative PCR (qPCR) (13). After extracting DNA from peripheral blood samples with the QIaAmp DNA Blood Mini Kit (QIAGEN) following the manufacturer’s instructions, the DNA was amplified with primers and probes (Applied Biosystems) complementary to specific sequences within the retroviral vector (15). The standard curve was established using serial dilutions of the plasmid encoding the transgene. Amplifications were performed using the ABI 7900HT Fast Real-Time PCR System (Applied Biosystems, Thermo Fisher Scientific) according to the manufacturer’s instructions.

Cytometric bead array and multiplex assays. We analyzed plasma or serum samples collected before and after κ.CART infusion using a BD cytokine cytometric bead array (CBA) kit (BD Pharmingen) or a Milliplex Kit (EMD Millipore), following the manufacturers’ instructions. In parallel with the samples, we used the human cytokine standards provided with the kits to prepare standard curves. The CBA assays were run using the BD FACSCalibur, and the data were analyzed from the Milliplex kits using the Luminex 200 System and Milliplex Analyst Software (EMD Millipore).

ELISpot assays. IFN-γ enzyme-linked immunospot (ELISpot) assays were performed to identify precursor T cells specific for known TAAs. PBMCs were plated at 2 × 104 to 4 × 105 per well in triplicate in 96 well Multiscreen plates (EMD Millipore), and IFN-γ production was measured in response to stimulation with peptide mixtures (pepmixes) consisting of 15-mer peptides overlapping by 11 aa and spanning the entire protein of interest for the following antigens: pp65, NY-ESO-1, MAGEA4, PRAME, and P53 (0.6 nmol of each peptide) (JPT Technologies). Descriptive statistics (means, median, ranges, and standard deviation or SEM) were used to summarize the data. The AUC was calculated using the trapezoidal rule. A 2-tailed Student’s t-test or nonparametric Wilcoxon rank-sum test for between-groups comparisons was performed, while the nonparametric Wilcoxon signed-rank test was applied for within-subjects comparisons. A P value of less than 0.05 was considered statistically significant.

Study approval. This study was approved by the US FDA, the Recombinant DNA Advisory Committee, and the IRB of the BCM and was conducted in accordance with Declaration of Helsinki principles. All participants provided written informed consent upon enrollment.

Author contributions
CAR, BS, BG, CMR, MKB, HEH, and GD conceptualized the overall strategy for the study and developed its clinical translation and implementation. The clinical protocol was written by CAR and MKB. CAR was the principal investigator of the protocol, and BG, MKB, and HEH were the investigational new drug (IND) sponsors. T cell manufacture, flow cytometry, and qPCR acquisition of clinical samples were performed by BB, HZ, OD, and EL, supervised by BS, and directed by APG and ZM. The manuscript was written by CAR, BS, MKB, and GD, and all authors discussed and interpreted the results. MHW and HL performed statistical analyses. CAR, GC, and RTK enrolled patients in the study and/or managed the patients, and VT was the study research nurse, assisting with enrollment, sample acquisition, and data safety monitoring of patients.

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