cells expressing anti–CD19 CARs, and Ag-specific eradication of normal B cells has been demonstrated.

Significant toxicities including hypotension, fevers, and renal insufficiency have occurred after infusions of anti–CD19-CAR–transduced T cells. Three patients with elevations in serum levels of inflammatory cytokines such as IFNγ after anti–CD19-CAR–transduced T-cell infusions have been reported; however, in one of these cases, the elevation in serum inflammatory cytokines was present before CAR-transduced T cells were infused. Determining the causes of elevated cytokine levels after anti–CD19-CAR–transduced T-cell infusions is not straightforward because only a small number of patients with elevated serum cytokine levels have been reported, and there are other possible causes of elevated serum cytokines such as sepsis. Inflammatory cytokines such as IFNγ and TNF (formerly known as TNFα) are produced by anti–CD19-CAR–transduced T cells in vitro; IFNγ and TNF can cause significant toxicity in humans; however, an association between inflammatory cytokine production by anti–CD19-CAR–transduced T cells and clinical toxicity has not been demonstrated. A better understanding of the relationship between cytokine production by CAR-transduced T cells and clinical toxicity is necessary to rationally plan future research aimed at increasing the safety of anti–CD19-CAR–transduced T cells.

We are conducting a clinical trial to assess the anti-malignancy efficacy, toxicity, and in vivo persistence of T cells transduced with
an anti-CD19 CAR. All of the patients on our clinical trial had advanced, progressive B-cell malignancies that were incurable by any standard treatment except allogeneic stem cell transplantation. Six of the 8 patients treated on our trial obtained objective remissions of their malignancies, and 4 of 8 patients had long-term elimination of CD19

/H11001

B-lineage cells. Significant toxicities that correlated with elevations in serum IFN

/H9253

and TNF occurred after infusions of anti–CD19-CAR–transduced T cells. In addition, we demonstrated CD19-specific IFN

/H9253

and TNF production by T cells from the blood of patients who had received infusions of anti–CD19-CAR–transduced T cells.

Methods

Clinical trial design

The trial was reviewed by the US Food and Drug Administration and the Institutional Review Board of the National Cancer Institute and allowed to proceed. Patients provided written informed consent before participation in this study in accordance with the Declaration of Helsinki. Patients underwent an apheresis to obtain PBMCs for producing anti–CD19-CAR–transduced T cells. Cyclophosphamide was administered daily on days 7 and 6 at a dose of 60 mg/kg. On days −5 through −1, patients received 25 mg/m² fludarabine daily. On day 0, patients received a single infusion of CAR-transduced T cells. Three hours after CAR-transduced T cells were administered, IL-2 was initiated. IL-2 was administered intravenously at a dose of 720 000 international units/kg every 8 hours until toxicity precluded additional doses. Remissions of chronic lymphocytic leukemia (CLL) or lymphoma were defined according to standard international criteria.33,34

Anti–CD19 CAR retroviral vector design

We previously reported the design and construction of the murine stem cell virus–based splice-gag vector (MSGV)–FMC63-28Z that encoded the anti-CD19 CAR used in our clinical trial.12

Anti–CD19–CAR–transduced T cell preparation

Anti–CD19–CAR–transduced T cells were prepared as described in supplemental Methods (available on the Blood Web site; see the Supplemental Materials link at the top of the online article) and as previously described.35

In vitro and ex vivo assays

Anti-Fab Ab staining and staining with labeled CD19 protein were used in flow cytometry to detect surface expression of the anti-CD19 CAR as described in the supplemental Methods. ELISAs, intracellular cytokine staining assays (ICCS), and CD107a degranulation assays were performed as described in supplemental Methods and as previously described.12,21 Serum ELISAs were carried out as described in supplemental Methods. Immunohistochemistry and flow cytometry were carried out as detailed in the supplemental Methods and as previously described.21

Real-time qPCR

Real-time quantitative PCR (qPCR) was carried out to determine the percentage of peripheral blood mononuclear cells containing the CAR gene as described in supplemental Methods.

Calculation of SOFA scores

The sequential organ failure assessment (SOFA) score is an established method of quantifying the overall severity of illness.36 The SOFA score includes an assessment of hypotension, the platelet count, and measurements of respiratory, liver, renal, and central nervous system function.36,37 We calculated daily SOFA scores for each patient by using clinical records from the day of CAR-transduced T-cell infusion and each of the first 10 days after CAR-transduced T-cell infusion.36 For each patient, the sum of the SOFA scores from each day was calculated to give the total SOFA score.36

Results

Production of anti–CD19-CAR–transduced T cells

Autologous PBMCs were stimulated with an anti-CD3 mAb OKT3 on day 0. The cells were transduced with gammaretroviruses encoding the anti-CD19 CAR on days 2 and 3. On day 10, a rapid expansion protocol was started, and the cells were ready for infusion on day 24. (B) Patients received 60 mg/kg cyclophosphamide chemotherapy daily for 2 days. Next, patients received 25 mg/m² fludarabine chemotherapy daily for 5 days. One day later, the patients received a single infusion of anti–CD19-CAR–transduced T cells. Starting on the same day as the T-cell infusion, the patients received IV IL-2 every 8 hours.

Figure 1. Anti–CD19-CAR–transduced T-cell production and clinical treatment protocols. (A) PBMCs were stimulated with the anti-CD3 mAb OKT3 on day 0. The cells were transduced with gammaretroviruses encoding the anti-CD19 CAR on days 2 and 3. On day 10, a rapid expansion protocol was started, and the cells were ready for infusion on day 24. (B) Patients received 60 mg/kg cyclophosphamide chemotherapy daily for 2 days. Next, patients received 25 mg/m² fludarabine chemotherapy daily for 5 days. One day later, the patients received a single infusion of anti–CD19-CAR–transduced T cells. Starting on the same day as the T-cell infusion, the patients received IV IL-2 every 8 hours.
expressing the anti-CD19 CAR at the time of infusion was 55% (Table 1). Most of the infused CAR-transduced cells were CCR7-negative, CD45RA-negative effector memory cells, but variable numbers of CCR7+, CD45RA-negative central memory cells were also present (Table 2). The CAR-expressing T cells specifically up-regulated CD107a when cultured with CD19-expressing target cells but not when cultured with negative control target cells that lacked CD19 expression (Figure 2B).

Table 1. Patient data

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age, y</th>
<th>Malignancy</th>
<th>No. of prior therapies</th>
<th>No. of infused cells/kg, ( \times 10^9 )</th>
<th>Percentage of infused cells CAR+</th>
<th>No. of infused CAR+ cells/kg, ( \times 10^7 )</th>
<th>Infused cells CD4/CD8 ratio</th>
<th>Doses of IL-2 administered</th>
<th>Response and time since treatment, mo*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a†</td>
<td>47</td>
<td>Follicular lymphoma</td>
<td>4</td>
<td>0.5</td>
<td>64</td>
<td>0.3</td>
<td>28/63</td>
<td>8</td>
<td>PR (7)</td>
</tr>
<tr>
<td>1b†</td>
<td>48</td>
<td>Follicular lymphoma</td>
<td>5</td>
<td>2.1</td>
<td>63</td>
<td>1.3</td>
<td>19/71</td>
<td>10</td>
<td>PR (18+)</td>
</tr>
<tr>
<td>2</td>
<td>48</td>
<td>Follicular lymphoma</td>
<td>5</td>
<td>0.5</td>
<td>65</td>
<td>0.3</td>
<td>23/73</td>
<td>9</td>
<td>NE (died with influenza)</td>
</tr>
<tr>
<td>3</td>
<td>61</td>
<td>CLL</td>
<td>3</td>
<td>2.5</td>
<td>45</td>
<td>1.1</td>
<td>35/53</td>
<td>2</td>
<td>CR (15+)</td>
</tr>
<tr>
<td>4</td>
<td>55</td>
<td>Splenic marginal zone lymphoma</td>
<td>3</td>
<td>2.0</td>
<td>53</td>
<td>1.1</td>
<td>72/24</td>
<td>4</td>
<td>PR (12)</td>
</tr>
<tr>
<td>5</td>
<td>54</td>
<td>CLL</td>
<td>4</td>
<td>0.6</td>
<td>50</td>
<td>0.3</td>
<td>87/12</td>
<td>2</td>
<td>SD (6)</td>
</tr>
<tr>
<td>6</td>
<td>57</td>
<td>CLL</td>
<td>7</td>
<td>5.5</td>
<td>30</td>
<td>1.7</td>
<td>37/57</td>
<td>1</td>
<td>PR (7)</td>
</tr>
<tr>
<td>7</td>
<td>61</td>
<td>CLL</td>
<td>4</td>
<td>5.4</td>
<td>51</td>
<td>2.8</td>
<td>58/41</td>
<td>2</td>
<td>PR (7+)</td>
</tr>
<tr>
<td>8</td>
<td>63</td>
<td>Follicular lymphoma</td>
<td>7</td>
<td>4.2</td>
<td>71</td>
<td>3.0</td>
<td>54/43</td>
<td>5</td>
<td>PR (8+)</td>
</tr>
</tbody>
</table>

PR indicates partial remission; NE, not evaluable; CR, complete remission; SD, stable disease; and CLL, chronic lymphocytic leukemia.

*Time since treatment is in months; + indicates an ongoing response as of the time of writing. The body surface area of each patient is given in supplemental Table 2.

†Patient 1 was treated twice. His first treatment has been previously reported (21).
Up-regulation of CD107a indicated degranulation, which is a prerequisite for perforin-mediated cytotoxicity. The CAR-transduced T cells produced IFNγ, TNF, and IL-2 in a CD19-specific manner (Figure 2D, Table 3).

Anti–CD19-CAR–transduced T cells can specifically recognize autologous leukemia cells

The blood of some of the patients on our trial contained large numbers of CD19+ CLL cells. Access to pretreatment blood samples from these patients allowed us to determine whether anti–CD19-CAR–transduced T cells could specifically recognize unmanipulated autologous CLL cells. The blood lymphocytes of patient 3 contained 64% CD19+ CLL cells before treatment on our protocol, and the blood lymphocytes of patient 6 contained 76% CD19+ CLL cells before treatment on our protocol. After treatment when the patients were in remission, the blood lymphocytes of both patient 3 and patient 6 contained only 0.1% CD19+ cells. As shown in Figure 2D and E, the anti–CD19-CAR–transduced T cells from each of these patients produced large amounts of IFNγ when cultured with the pretreatment lymphocytes that were mostly leukemia cells, but the CAR-transduced T cells produced only background levels of IFNγ when cultured with the lymphocytes that were obtained after treatment when the patients were in remission. IFNγ was not produced by the leukemia cells of either patient (data not shown).

Six of the 8 treated patients obtained objective remissions

The 8 patients treated on our protocol had either B-cell lymphoma or CLL (Table 1). The patients all had progressive malignancy at the time of enrollment on our protocol (Figure 3A). Ninety-six percent of the blood B cells were CLL cells. In addition, 50%–60% of his cellular BM was CLL (Figure 3B-C). A prominent clonal leukemia population that expressed the characteristic CD19+ and CD5+ phenotype of CLL was detected by flow cytometry of BM cells before treatment on our protocol (Figure 2A).

Table 2. Memory phenotype of infused anti-CD19 CAR-expressing T cells

<table>
<thead>
<tr>
<th>Patient</th>
<th>CD62L</th>
<th>CCR7+CD45RA+</th>
<th>CCR7+CD45RA-</th>
<th>CCR7-CD45RA+</th>
<th>CCR7-CD45RA-</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a*</td>
<td>21</td>
<td>7</td>
<td>30</td>
<td>53</td>
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<tr>
<td>1b*</td>
<td>20</td>
<td>8</td>
<td>20</td>
<td>55</td>
<td>18</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>5</td>
<td>21</td>
<td>61</td>
<td>13</td>
</tr>
<tr>
<td>3</td>
<td>27</td>
<td>1</td>
<td>8</td>
<td>87</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>35</td>
<td>0</td>
<td>5</td>
<td>90</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>26</td>
<td>3</td>
<td>13</td>
<td>71</td>
<td>13</td>
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<tr>
<td>6</td>
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<td>6</td>
<td>27</td>
<td>57</td>
<td>10</td>
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<tr>
<td>7</td>
<td>4</td>
<td>4</td>
<td>27</td>
<td>60</td>
<td>9</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>1</td>
<td>9</td>
<td>81</td>
<td>8</td>
</tr>
</tbody>
</table>

The phenotype of the infused CD19 CAR-expressing T cells was determined by flow cytometry. Values are the percentage of the CAR+ CD3+ cells that expressed the indicated markers.

*Patient 1 was treated twice.

Table 3. Cytokine production by infused cells

<table>
<thead>
<tr>
<th>Patient</th>
<th>IFNγ, pg/mL</th>
<th>TNF, pg/mL</th>
<th>IL-2, pg/mL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CD19-positive target</td>
<td>CD19-negative target</td>
<td>CD19-positive target</td>
</tr>
<tr>
<td>1*</td>
<td>8190</td>
<td>448</td>
<td>1156</td>
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<tr>
<td>2</td>
<td>9850</td>
<td>6250</td>
<td>2002</td>
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<tr>
<td>3</td>
<td>19000</td>
<td>9312</td>
<td>1683</td>
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<tr>
<td>4</td>
<td>27900</td>
<td>21 895</td>
<td>2768</td>
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<td>5</td>
<td>36700</td>
<td>21 515</td>
<td>2421</td>
</tr>
<tr>
<td>6</td>
<td>14 800</td>
<td>8288</td>
<td>798</td>
</tr>
<tr>
<td>7</td>
<td>29 300</td>
<td>21 980</td>
<td>1661</td>
</tr>
<tr>
<td>8</td>
<td>9960</td>
<td>9830</td>
<td>1697</td>
</tr>
</tbody>
</table>

Levels of the indicated cytokines were determined by standard ELISAs after an overnight culture of T cells from the time of infusion with either CD19-positive target cells or CD19-negative target cells. NGFR-K562 cells were used as CD19-negative target cells for all cultures. CD19-K562 cells were used as CD19-positive targets for the cultures preceding the TNF ELISAs. NALM6 cells were used as the CD19-positive target cells for the cultures preceding the IFNγ and IL-2 ELISAs.

*Results are from the second treatment of patient 1.
After treatment, CLL was completely eradicated from the blood of patient 3, and the number of polyclonal blood B cells has stayed at below-normal levels of 17 to 40 B cells/μL for 15 months (lower limit of the normal 61 B cells/μL; Figure 3A). Patient 3’s blood B cells that have returned after treatment were determined to be polyclonal by flow cytometry staining for Igκ and λ proteins (data not shown). CLL was eliminated from the BM of patient 3 after treatment as shown by BM IHC staining (Figure 3B-C) and by multicolor flow cytometry analysis of the BM cells (Figure 3D). B-lineage cells were nearly absent from the BM, but other hematopoietic cells had recovered (Figure 3B-C). Overall, the cellularity of the BM varied between 20% and 70%. A normal BM cellularity for a 61-year-old patient is ~40%. Patient 3 continues in complete remission > 15 months after treatment on our protocol.

**Patient 7 had a substantial reduction in adenopathy after CAR-transduced T-cell infusion**

Before enrollment on our protocol, patient 7 had CLL that was progressive despite 4 prior therapies. Extensive regression of adenopathy occurred during the time between a pretreatment computed tomography (CT) scan and a second CT scan that was performed 32 days after treatment (Figure 4A). Regression of the adenopathy continued between day 32 and day 132 after the CAR-transduced T-cell infusion. This continued regression, which occurred > 33 days after the last dose of chemotherapy suggested that the CAR-transduced T cells contributed to the regression of the adenopathy. In accordance with this possibility, anti–CD19-CAR–transduced T cells persisted in the blood of patient 7 until at least day 132 after infusion (Figure 5B). Because the patient received chemotherapy before the CAR-transduced T cells, an alternative explanation for the decreasing adenopathy between day 32 and 132 after CAR-transduced T-cell infusion is continued resolution of adenopathy because of clearance of leukemia cells that were killed by the chemotherapy.

**Patient 8 had a prolonged specific eradication of normal B cells**

Patient 8 had a normal level of polyclonal blood B cells before treatment on our protocol. After treatment, his blood B cells have been eliminated for 26 weeks as of his last follow-up.
The B-cell depletion in patient 8 was specific because blood T cells (Figure 4C) and NK cells (Figure 4D) recovered shortly after treatment. This specific, long-term elimination of normal CD19\(^+\)/H11001 B cells indicates that anti–CD19-CAR–transduced T cells are destroying cells expressing the targeted CD19 Ag in vivo. Notably, this long-term elimination of B cells cannot be attributed to the chemotherapy that the patient received because we have previously shown that patients receiving the same chemotherapy regimen plus infusions of T cells targeting Ags that are not expressed on B cells recover normal blood B cell numbers in 8 to 19 weeks.\(^{21}\) Overall, we have noted B-cell depletion lasting at least 6 months in 4 of the 8 patients treated on our protocol. As previously reported, patient 1 had a complete eradication of blood and BM B-lineage cells for 36 weeks after his first infusion of anti–CD19-CAR–transduced T cells.\(^{21}\) Nine weeks after his second treatment, patient 1 was found to have a normal number of polyclonal blood B cells. The reason for this recovery of normal B cells is unknown. We have noted prolonged B-cell depletion that lasted at least 6 months in 3 additional patients. Patient 7 had no detectable blood B cells at his last follow-up 7 months after infusion of anti–CD19-CAR–transduced T cells. The prolonged depressions of blood B cell numbers in patient 3 and patient 8 are shown in Figures 3A and 4B, respectively. For all patients, the blood B-cells were quantitated 4 to 5 months after CAR-transduced T-cell infusion (supplemental Table 1).

**Varied levels of anti–CD19-CAR–transduced T cells could be detected in the blood of all patients**

To quantitate anti–CD19-CAR–transduced T cells in the blood of patients, we developed a qPCR assay that specifically detected the DNA sequence of the anti-CD19 CAR. Data from these quantitative PCR experiments were expressed as a percentage of total PBMCs that contained the anti-CD19 CAR gene. The persistence of cells containing the CAR gene varied widely, but in patient 1 through patient 6, cells containing the CAR gene could be detected at levels > 0.01% of total PBMCs for 20 days (Figure 5A). In contrast, patient 7 and patient 8 had high peak percentages and long-term persistence of PBMCs containing the CAR gene (Figure 5B). We confirmed the high levels of CAR-expressing cells in the blood of patient 7 and patient 8 by detecting CAR-expressing T cells with flow cytometry after staining with labeled CD19 protein (Figure 5C and D). We also detected cells containing the CAR gene in the BM of patient 7 and patient 8. As measured by qPCR, 0.03% of the BM cells of patient 7 contained the CAR gene 14 weeks after CAR-transduced T-cell infusion, and 0.13% of the BM cells of patient 8 contained the CAR gene 8 weeks after CAR-transduced T-cell infusion.

**T cells that degranulated in a CD19-specific manner were detected in the blood of patient 7 ex vivo**

We demonstrated the presence of functional CD19-specific T cells in the blood of patient 7 by detecting T cells that up-regulated CD107a in a CD19-specific manner after anti–CD19-CAR–transduced T-cell infusion but not before CAR-transduced T-cell infusion (Figure 5E).

**Patients experienced significant toxicity that correlated with elevated levels of IFN\(_{\gamma}\) and TNF**

As mentioned previously, 4 of the 8 patients on our clinical trial had long-term depletion of normal B cells. In accordance with an eradication of B-lineage cells, all of these 4 patients have developed hypogammaglobulinemia and have subsequently been treated...
patients could be divided into 2 groups. One group, which included multiple time-points after treatment (Figure 6). We found that the CAR-transduced T-cell infusions, we performed ELISAs for IFN-γ and TNF in a CD19-specific manner in vitro. For example, TNF is a potent inducer of hypotension. We have previously reported a patient who received an infusion of T cells transduced with an anti-ERBB2 (human epidermal growth factor receptor-2)–specific CAR without administration of exogenous IL-2.30,31 We hypothesized that much of the toxicity that occurred in our patients was because of elevations in inflammatory cytokines such as IFN-γ and TNF. To quantify the toxicity experienced by our patients, we calculated SOFA scores for each patient.36,37 The SOFA score is an established method of sequentially quantifying the severity of illness in a patient. The SOFA score is calculated with measurements of blood pressure, respiratory function, renal function, hepatic function, central nervous system function, and the blood platelet count.36,37 The SOFA score increases as the severity of illness increases. We calculated SOFA scores for the day of infusion and each of the first 10 days after infusion for each patient. The sum of the SOFA scores from each day was calculated to give the total SOFA score for each patient. The patients with prominent elevations in serum IFN-γ and TNF after CAR-transduced T-cell infusion had a mean total SOFA score of 105.0, and patients without elevations in serum IFN-γ and TNF had a mean total SOFA score of 61.5 (P = .016, 2-tailed t test). We tested for an association between the total SOFA scores of each patient and the areas under the curves of each patient’s serum IFN-γ and TNF levels versus time. The total SOFA scores of each patient correlated with the areas under the curves of each patient’s serum IFN-γ and serum
TNF levels versus time ($P = .02$ for IFNγ and $P = .001$ for TNF; Figure 6E-F). Notably, in 3 of the 4 patients with prominent elevations of serum inflammatory cytokines after anti–CD19-CAR–transduced T-cell infusions, new elevations in serum IFNγ and TNF along with severe toxicity occurred 4 or more days after the patient’s last dose of exogenous IL-2. Because toxicities and elevations in serum cytokines associated with exogenous IL-2 usually improve within a few days after IL-2 treatment ceases, the elevated serum inflammatory cytokines and toxicities observed in these patients were probably not because of the exogenous IL-2.$^{41-43}$ In addition, during the first 12 days after CAR-transduced T-cell infusion, none of the 4 patients with elevated inflammatory cytokines had proven infections that could have caused sepsis, which is associated with elevations in serum inflammatory cytokines.$^{28}$

**T cells that produced inflammatory cytokines in a CD19-specific manner were detected in the blood of multiple patients after anti–CD19-CAR–transduced T-cell infusions**

Because CAR-transduced T cells produced IFNγ, TNF, and IL-2 in a CD19-specific manner in vitro (Figure 2C, Table 3), the infused cells might have produced inflammatory cytokines in vivo when the CAR-expressing T cells contacted normal and malignant CD19$^+$ B cells in our patients. We hypothesized that CAR-transduced T cells were a source of the inflammatory cytokines detected in the serum of some of the patients on our trial. We obtained PBMCs from patients before and after infusion of

**Table 4. Toxicities**

<table>
<thead>
<tr>
<th>Patient</th>
<th>Toxicities$^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1‡‡</td>
<td>Fatigue, herpes zoster with secondary otitis externa 6 months after treatment</td>
</tr>
<tr>
<td>2</td>
<td>Escherichia coli bacteremia, died with influenza pneumonia, dyspnea, hypoxemia, nonbacterial thrombotic endocarditis, cerebral infarction, elevated liver enzymes</td>
</tr>
<tr>
<td>3</td>
<td>Hypotension, acute renal failure, hypoxemia, hyperbilirubinemia, capillary leak syndrome</td>
</tr>
<tr>
<td>4</td>
<td>Diarrhea, fatigue</td>
</tr>
<tr>
<td>5</td>
<td>Fever, fatigue, hypotension</td>
</tr>
<tr>
<td>6</td>
<td>Hypotension, capillary leak syndrome, hypobulinemia</td>
</tr>
<tr>
<td>7</td>
<td>Obstructive jaundice, acute renal failure, hyperbilirubinemia, capillary leak syndrome, anorexia, elevated liver enzymes, electrolyte abnormalities</td>
</tr>
<tr>
<td>8</td>
<td>Hypotension, obtundation, acute renal failure, capillary leak syndrome, headache, pleural effusion, electrolyte abnormalities</td>
</tr>
</tbody>
</table>

$^*$All grade 3 and 4 toxicities by the Cancer Therapy Evaluation Program Common Terminology Criteria for Adverse Events Version 3, are listed.

$^*$All patients had pancytopenia with chemotherapy.

$^\dagger$Patient 1 was treated twice. Only his second treatment is reported here. The first treatment has been previously reported (21).

Figure 6. Elevations in serum levels of IFNγ and TNF occurred in some patients after infusions of anti–CD19-CAR–transduced T cells. (A) Patients 1, 2, 4, and 5 did not have prominent elevations of serum IFNγ after cell infusion. (B) Patients 3, 6, 7, and 8 had prominent elevations of serum IFNγ after cell infusion. (C) Patients 1, 2, 4, and 5 did not have prominent elevations of serum TNF after cell infusion. (D) Patients 3, 6, 7, and 8 had prominent elevations of serum TNF after cell infusion. For panels A through D, day 0 is the day of CAR-transduced T-cell infusion, and serum IFNγ and TNF were determined by standard ELISAs performed on serum samples. (E) The correlation between the total sequential organ failure assessment (SOFA) scores of each patient and the areas under the curves of each patient’s serum IFNγ level (pg/mL x days) from the day of CAR-transduced T-cell infusion until day 11 after T-cell infusion is shown. The total SOFA scores and the areas under the curves of each patient’s serum IFNγ level (pg/mL x days) from the day before CAR-transduced T-cell infusion until day 12 after T-cell infusion is shown. The total SOFA scores and the areas under the curves of serum TNF were correlated (Pearson $r = 0.9$, $P = .001$).
anti–CD19-CAR–transduced T cells. The PBMCs were stimulated for 6 hours with CD19-K562 cells that expressed CD19, a population of CD4+ cells that produced IFNγ was detected; in contrast, when the PBMCs were cultured with the control cells NGFR-K562 that lack CD19 expression, T cells did not produce IFNγ. PBMCs collected before the anti–CD19-CAR–transduced T-cell infusion did not produce IFNγ after incubation with either CD19-K562 or NGFR-K562. Plots are all gated on CD3+ lymphocytes. (B) PBMCs were collected from patient 7, 18 days after infusion of CAR-transduced T cells. When the PBMCs were cultured for 6 hours with CD19-K562 cells that expressed CD19, T cells that produced IFNγ, TNF, and IL-2 were detected. When the PBMCs were cultured with the control cells NGFR-K562 that lack CD19 expression, T cells did not produce IFNγ, TNF, or IL-2. PBMCs collected before the anti–CD19-CAR–transduced T-cell infusion did not produce IFNγ, TNF, or IL-2 after incubation with either CD19-K562 or NGFR-K562. Plots are all gated on CD3+ lymphocytes.

**Figure 7.** Large numbers of T cells producing cytokines in a CD19-specific manner can be detected in the blood of patients after anti–CD19-CAR–transduced T-cell infusions. (A) PBMCs were collected from patient 3, 14 days after infusion of CAR-transduced T cells. When the PBMCs were cultured for 6 hours with CD19-K562 cells that expressed CD19, a population of CD4+ cells that produced IFNγ was detected; in contrast, when the PBMCs were cultured with the control cells NGFR-K562 that lack CD19 expression, T cells did not produce IFNγ. PBMCs collected before the anti–CD19-CAR–transduced T-cell infusion did not produce IFNγ after incubation with either CD19-K562 or NGFR-K562. Plots are all gated on CD3+ lymphocytes. (B) PBMCs were collected from patient 7, 18 days after infusion of CAR-transduced T cells. When the PBMCs were cultured for 6 hours with CD19-K562 cells that expressed CD19, T cells that produced IFNγ, TNF, and IL-2 were detected. When the PBMCs were cultured with the control cells NGFR-K562 that lack CD19 expression, T cells did not produce IFNγ, TNF, or IL-2. PBMCs collected before the anti–CD19-CAR–transduced T-cell infusion did not produce IFNγ, TNF, or IL-2 after incubation with either CD19-K562 or NGFR-K562. Plots are all gated on CD3+ lymphocytes.

**Discussion**

We studied 8 patients with advanced, progressive B-cell malignancies on a clinical trial of chemotherapy followed by an infusion of anti–CD19-CAR–transduced T cells and a course of IV IL-2. Six of the 7 evaluable patients studied on our trial obtained strictly defined remissions of their malignancies.33,34 Four of the 6 remissions are ongoing at the time of last follow-up (Table 1). B cells were depleted from the blood of 4 of the 8 patients for at least 6 months after anti–CD19-CAR–transduced T-cell infusions (Figures 3A, 4B). The duration of normal B-cell depletion in these 4 patients exceeded the duration of the B-cell depletion that occurs because of the chemotherapy regimen that the patients received,21 so we can conclude that the anti–CD19-CAR–transduced T cells destroyed normal CD19+ B cells in vivo. The depletion of normal CD19+ B cells suggests that the
The evidence that lymphocyte-depletion enhances adoptive T-cell therapy is based on the results from experiments demonstrating the critical importance of lymphocyte-depletion before adoptive transfer of syngeneic anti-CD19-CAR–transduced T cells in mice. In this study, all mice that were lymphocyte-depleted with total body irradiation before lymphoma challenge and anti-CD19–CAR–transduced T-cell infusion survived without any persisting lymphoma and without any normal B cells; in contrast, mice challenged with lymphoma and treated with anti-CD19–CAR–transduced T cells without lymphocyte depletion all died of lymphoma. These results are consistent with other reports that have shown a dramatic enhancement of adoptive T cell therapies of melanoma by lymphocyte depletion before T cell transfer. In addition, treatment of B-cell malignancies with CAR-transduced T cells in mice was enhanced by elimination of endogenous B cells. In accordance with these murine results, a total of 9 patients have been reported who did not receive lymphocyte-depleting therapy before infusions of T cells transduced with anti-CD19 CARs that contained a CD28 domain, and none of these patients had objective remissions of their malignancies. The evidence that lymphocyte-depletion enhances adoptive T cell therapy plus the known efficacy of chemotherapy and radiotherapy against B-cell malignancies argue for lymphocyte depletion before infusion of anti-CD19-CAR–transduced T cells.

Our trial included a course of IV IL-2 that was administered after the anti-CD19-CAR–transduced T cells. Exogenous IL-2 can cause toxicities similar to the toxicities that we have observed in our patients; however, the severity of toxicity experienced by patients on our trial did not correlate with the number of doses of IL-2 that the patients received (data not shown). In addition, 3 of the 4 patients on our trial with significant toxicities associated with elevations in serum inflammatory cytokines had severe toxicities and prominent new increases in serum inflammatory cytokines that occurred 4 or more days after IL-2 administration ceased. Because most of the toxicities caused by IV IL-2 rapidly resolve after IL-2 administration ceases, the IV IL-2 was probably not a major cause of the toxicities and elevated cytokine levels in these patients 4 or more days after cessation of IL-2 infusions; however, the IV IL-2 could have contributed to toxicities experiences by our patients during the time of IL-2 administration, and we are amending our protocol to eliminate IL-2 administration. In mice, administration of IL-2 has been shown to enhance production of IFNγ by tumor-specific T cells. Therefore, the possibility exists that exogenous IL-2 could enhance production of inflammatory cytokines by CAR-expressing T cells in humans.

A central question for future CAR research is how to minimize toxicity while maximizing anti-malignancy efficacy. We have shown that toxicity correlates with serum inflammatory cytokine levels after CAR-transduced T-cell infusions, so reducing inflammatory cytokine levels in patients receiving infusions of CAR-transduced T cells is a promising approach to decreasing toxicity. Including the signaling domain of 4-1BB rather than the signaling domain of CD28 in CARs has been suggested as a way to decrease cytokine-mediated toxicity. Use of 4-1BB in CARs is a promising approach that needs further investigation, but other alterations in signaling chains should also be explored with a goal of decreasing inflammatory cytokines such as TNF while maintaining or enhancing anti-malignancy efficacy. We showed that the infused anti-CD19–CAR–transduced T cells produced large amounts of IFNγ when cultured in vitro with pretreatment PBMCs that contained large numbers of CD19+ CLL cells; in contrast, the CAR-transduced T cells produced minimal amounts of IFNγ when cultured with remission PBMCs lacking CD19+ cells; however, the IV IL-2 could have contributed to toxicities experienced by patients. In addition, we demonstrated ex vivo CD19–specific production of inflammatory cytokines by T cells from the blood of patients after anti-CD19–CAR–transduced T-cell infusions (Figure 7). These findings suggest that a promising approach to reducing toxicity associated with CD19–specific cytokine production by CAR-transduced T cells is to minimize the number of CD19+ cells encountered by the CAR–transduced cells. This could be accomplished by only administering CAR-transduced T cells to patients with small disease burdens and by treating patients with B-cell depleting mAbs such as the anti-CD20 mAb rituximab before infusions of anti-CD19–CAR–transduced T cells. Another possible way to reduce acute toxicities after CAR-transduced T-cell infusions is to administer multiple smaller doses of CAR-transduced T cells rather than one large dose of cells. Suicide genes that allow for rapid depletion of genetically modified cells might provide an added measure of safety to CAR-transduced T-cell therapies. An additional strategy for reducing toxicity is to administer anti-TNF agents such as etanercept during episodes of severe toxicity.

Our results demonstrate a powerful ability of anti-CD19-CAR–transduced T cells to eradicate CD19+ cells in humans, but cytokine-associated toxicities occurred after infusions of CAR-transduced T cells. Improvements in adoptive T-cell therapy with CAR-transduced T cells can be expected as investigations into CAR design and clinical application of CAR-transduced T cells continue. Adoptive transfer of genetically modified Ag-specific T cells has great potential to become an important part of the treatment of B-cell malignancies in the near future.

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**Authorship**


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B-cell depletion and remissions of malignancy along with cytokine-associated toxicity in a clinical trial of anti-CD19 chimeric-antigen-receptor–transduced T cells


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