Biomarker correlates with response to NY-ESO-1 TCR T cells in patients with synovial sarcoma

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Autologous T cells transduced to express a high affinity T-cell receptor specific to NY-ESO-1 (letetresgene autoleucel, lete-cel) show promise in the treatment of metastatic synovial sarcoma, with 50% overall response rate. The efficacy of lete-cel treatment in 45 synovial sarcoma patients (NCT01343043) has been previously reported, however, biomarkers predictive of response and resistance remain to be better defined. This post-hoc analysis identifies associations of response to lete-cel with lymphodepleting chemotherapy regimen (LDR), product attributes, cell expansion, cytokines, and tumor gene expression. Responders have higher IL-15 levels pre-infusion (p = 0.011) and receive a higher number of transduced effector memory (CD45RA - CCR7-) CD8+ cells per kg (p = 0.039). Post-infusion, responders have increased IFNγ, IL-6, and peak cell expansion (p < 0.01, p < 0.01, and p = 0.016, respectively). Analysis of tumor samples post-treatment illustrates lete-cel infiltration and a decrease in expression of macrophage genes, suggesting remodeling of the tumor microenvironment. Here we report potential predictive and pharmacodynamic markers of lete-cel response that may inform LDR, cell dose, and strategies to enhance anticancer efficacy.

Chimeric antigen receptor (CAR) T-cell therapies have revolutionized the treatment for hematologic malignancies1,2, but have shown limited efficacy in solid tumors3. Clinical activity in solid tumors, including metastatic HPV-associated carcinomas, melanomas, synovial sarcomas (SS), and myxoid/round cell liposarcomas (MRCLS), has been observed with engineered T-cell receptor (TCR) T cells4–9. In contrast to CAR T cells which recognize cell surface antigens, TCR T cells are engineered with a TCR specific for peptides from intracellular cancer antigens presented by a human leukocyte antigen (HLA) molecule10. Letetresgene autoleucel (lete-cel; GSK3377794) consists of autologous CD4+ and CD8+ T-cells transduced with a high-affinity TCR recognizing the NY-ESO-1 (New York esophageal squamous cell carcinoma 1)
antigen in complex with specific HLA-A*02 alleles. NY-ESO-1-specific TCR T cells have shown robust clinical efficacy in SS. One clinical trial of retrovirally transduced NY-ESO-1 TCR T cells with interleukin (IL)–2 treatment (NCT00670748) demonstrated objective clinical responses in 61% of patients with SS, and study NCT01343043 identified anti-tumor responses in up to 50% of advanced SS patients treated with let-epoT.

SS is characterized by an SS8-SXX1, 2, or 4 fusion protein formed by chromosomal translocations at t(X; 18)[p11.2;q11]. This, in the proper cell context, drives malignant transformation via epigenetic disturbances of the SWI/SNF complex. The translocation also causes aberrant upregulation of NY-ESO-1, which is expressed in ~80% of SS tumors. SS tumors have been characterized as immune deserts with exceptionally low immune cell infiltration compared with other solid tumor subtypes. Macrophages are the predominant infiltrates and are associated with poor prognosis in SS. Poor immune cell infiltration, coupled with low tumor HLA expression and mutational burden, likely render SS less susceptible to non-cellular immunotherapies, with rare responses observed with immune checkpoint inhibitors. The challenges associated with immunotherapies in SS underscore the significance of the clinical responses reported with TCR T cell therapies. To further increase treatment efficacy, it is necessary to identify cell product characteristics and biomarkers predictive of response. Peak cell expansion and cytokine levels on day of and post-infusion have been linked to response or remission to CAR T cells in hematologic malignancies. However, few biomarker correlates have been identified for solid tumors with engineered cell therapies. We report findings from a post-hoc analysis of study NCT01343043, identifying specific attributes of lymphodepleting chemotherapy regimens (LDRs), cell dose, and cell product which impact in vivo cell expansion and correlate with clinical response. We also report preliminary findings on the role of LDR in SS. Study findings from this comprehensive dataset contribute towards the progressive understanding of mechanisms of response and resistance to TCR T-cell therapy in SS, a model for solid tumors, and provide considerations for further immunotherapy developments.

Results

Standard LDR creates favorable conditions for infused T cells and highlights benefits of higher cell dose

Patients with advanced or metastatic SS were enrolled to four cohorts designed to evaluate the impact of varying NY-ESO-1 expression levels and LDR on response (Table 1). Baseline patient characteristics were similar across cohorts (Table S1). The primary endpoint was overall response rate as assessed by investigators and was 50% in Cohort 1, as previously reported by D’Angelo et al., 31% in Cohort 2, 20% in Cohort 3, and 27% in Cohort 4 (Table 1). Review by an independent committee was performed as a sensitivity analysis and the results agreed with a high concordance of 89%. Response rates were unchanged for Cohorts 1 and 3 and increased to 46% and 47% in cohorts 2 and 4 respectively (Table 1). The secondary efficacy endpoints included best overall response, duration of response (DoR), progression-free survival (PFS) and overall survival (OS). Best overall response and DoR were previously reported by D’Angelo et al. and Ramachandran et al. for all cohorts. Here we report median DoR ranging from 8.6 to 32.1 weeks, median PFS ranging from 8.6 to 22.4 weeks and median OS ranging from 9.9 to 26.2 months across cohorts (Table 1). The safety profile of Cohort 1 was previously reported by D’Angelo et al. Here we report on safety events across all cohorts. Observed safety events were expected and consistent with lymphodepletion and T-cell activation, including cytoopenias and cytokine release syndrome (Table S2, Table S3). Eleven patients were eligible for a second infusion of let-epo. Two patients responded post second infusion, while the remaining patients had stable disease with evidence of changes in tumor size (Table S4). This exploratory, post-hoc analysis focuses on correlates of post-first infusion and considers responders as patients whose tumors had a partial or complete response as assessed by investigators. Biomarker associations presented here that are significant with investigator-assessed response remained significant when analyzed with response as assessed by independent review committee.
Cell dose was not associated with PFS (Fig. S3g). These data further support the use of a standard LDR and the benefits of providing a higher cell dose/kg, when possible, to enable T cell expansion post infusion in synovial sarcoma.

Responders received lete-cel product enriched with activated, effector memory CD8 cells and containing comparable total CD8 to CD4 cell ratio

Lete-cel contains a mixture of transduced and non-transduced T cells. In this study, the median transduction efficiency was 35% (range 14–63%). To characterize the transduced cells, we used an NY-ESO-1 major histocompatibility complex (MHC) class I pentamer reagent. This pentamer is primarily used to stain CD8 cells due to co-receptor stabilization, therefore our analysis focused on CD8+ Pentamer+ cells.

On average, responders had 28% CD8+ Pentamer+ cells with an effector memory (EM) phenotype (CD45RA−CCR7−) (Fig. S4a, b). Since cell dose/kg has been shown to have an impact on response (Fig. 1e), we consider it important to analyze the absolute number of cells per phenotype infused. Notably, responders received a higher number of CD8+ Pentamer+ EM cells/kg, with a median of 12 million/kg compared to 4 million/kg for non-responders (Fig. 3a). No significant difference in other memory phenotype cells, such as T stem cell memory (TSCM) or central memory (CM), received by responders and non-responders, was observed in this study. A similar trend was observed when further analyzed as a logistic regression (Fig. S4c). Additionally, the number of CD8+ EM and CM cells infused were associated with Cmax (p = 0.0094 and p = 0.0017, respectively) (Fig. 3b). As T cells differentiate from naïve to terminal effector cells, their specialized function drives production of certain cytokines. We analyzed the relationship between infused memory phenotypes and levels of interferon (IFN)γ, a key cytokine for promoting host-immune recruitment to tumors. Figure 3c shows an association between the number of CD8+ EM cells infused and peak IFNγ post-infusion (p = 0.019). This is an interesting finding, suggesting a link between the product phenotype and the functionality of these cells post-infusion.

To better understand factors that affect product attributes, the impact of the starting apheresis material was evaluated. There was a significant association between percent CD8+ EM and CD4 cell ratio with >30% CD8+ EM (Fig. 3d, Fig. S4d). This highlights the possibility of the apheresis material to influence product characteristics and potentially identify patients who are more likely to respond. Further analysis is needed to identify patient characteristics that may influence the starting proportion of EM cells.

Together these findings demonstrate that CD8+ EM cells are important for lete-cel response in SS. When the impact of CD8+ EM cells on PFS was analyzed, there was only a trend toward increased PFS with higher percentage and number of infused cells/kg (p = 0.055 and p = 0.072, respectively) (Fig. 4a). This points to additional factors or cell populations which may be needed to achieve prolonged response.

### Table 1 | Summary of efficacy results across study cohorts

| Parameter | Cohort 1 (n = 12) | Cohort 2 (n = 13) | Cohort 3 (n = 5) | Cohort 4 (n = 15) |
|-----------|------------------|------------------|-----------------|------------------|
| **NY-ESO-1 Expression (IHC Score)** | HIGH 2 or 3+ in ≥50% of tumor cells | LOW 1+ in ≥1% cells but not exceeding 2+ or 3+ in ≥50% cells | HIGH 2 or 3+ in ≥50% of tumor cells | **LYMPHODEPLETION REGIMEN** |
| **Median transduced cell dose (10^9)** | 3.60 (0.45–14.36) | 2.42 (1.60–5.01) | 3.02 (1.53–5.00) | 2.40 (1.00–4.95) |
| **Investigator Assessed (Primary Endpoint)** | Overall response rate (%) | Complete Response | Partial Response | Stable Disease | Progressive Disease | Not evaluable | Median DoR (weeks) | Median PFS (months) | Median OS (months) | Independent Review Committee |
| **(95% CI)** | Overall response rate (%) | Complete Response | Partial Response | Stable Disease | Progressive Disease | Not evaluable | Median DoR (weeks) | Median PFS (months) | Median OS (months) | Overall response rate (%) |
| | 6 (50%) | 1 (8%) | 5 (42%) | 5 (42%) | 1 (8%) | 0 | 31.0 (13–72) | 15.4 (7.7–38.0) | 24.3 (8.5–48.8) | 6 (50%) |
| | 4 (31%) | 0 | 4 (31%) | 7 (54%) | 1 (8%) | 1 | 8.6 (6–13) | 13.1 (7.9–13.9) | 9.9 (3.9–19.6) | 6 (50%) |
| | 1 (20%) | 0 | 4 (27%) | 3 (60%) | 0 | 1 (8%) | 32.1 (22–32) | 8.6 (0.7–36.1) | 19.9 (8.8–NA) | 4 (27%) |
| | 4 (27%) | 0 | 4 (27%) | 10 (67%) | 1 (7%) | 0 | 16.4 (14–94) | 22.4 (13.3–26.6) | 26.2 (9.2–40.6) | 7 (8%) |
| **Best Overall Response (%)** | Not available | Not available | Not available | Not available | Not available | Not available | Not available | Not available | Not available | Not available |
| **(95% CI)** | Overall response rate (%) | Not available | Not available | Not available | Not available | Not available | Not available | Not available | Not available | Not available |
| | 0.21–0.79 | 0.21–0.79 | 0.21–0.79 | 0.21–0.79 | 0.21–0.79 | 0.21–0.79 | 0.21–0.79 | 0.21–0.79 | 0.21–0.79 | 0.21–0.79 |
| **Proportion of patients with a confirmed CR or PR** | Not evaluable | Not evaluable | Not evaluable | Not evaluable | Not evaluable | Not evaluable | Not evaluable | Not evaluable | Not evaluable | Not evaluable |
| **(95% CI)** | Not evaluable | Not evaluable | Not evaluable | Not evaluable | Not evaluable | Not evaluable | Not evaluable | Not evaluable | Not evaluable | Not evaluable |
| | 0.21–0.79 | 0.21–0.79 | 0.21–0.79 | 0.21–0.79 | 0.21–0.79 | 0.21–0.79 | 0.21–0.79 | 0.21–0.79 | 0.21–0.79 | 0.21–0.79 |

CI confidence interval, DoR duration of response, NA not available, OS overall survival, PFS progression-free survival, IHC immunohistochemistry, NY-ESO-1, New York esophageal squamous cell carcinoma.

Data modified intent-to-treat population: all patients that received lete-cel infusion.

Proportion of patients with a confirmed CR or PR relative to total number of patients with 95% Clopper-Pearson confidence intervals.

Recorded from the time of first T-cell infusion until disease progression.

Data from Long-Term Follow-up Study, cut-off April 23, 2021.

Review by an independent committee was performed as a sensitivity analysis for the primary endpoint which was based on investigator assessment.

PFS was defined as the time from T-cell infusion to the earliest documentation of disease progression or death from any cause or surgical resection or start of prohibited medication.

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At Week 4, responders had higher levels of CD8+ Pentamer+ cells (Fig. 4b), consistent with DNA-based persistence results (Fig. 2d, S5a). Of these remaining cells, ~50% were characterized by a T naïve/stem-like phenotype (CD45RA + CCR7+) (Fig. 4c), suggesting this cell type may be beneficial for long-term persistence.

Further analysis of the product revealed responders received cells characterized by an activated phenotype and comparable ratio of total CD8+ to CD4+. Cells expressed CD40 ligand (CD40L) which was associated with an EM phenotype (Fig. S5b, c). There was no association of PD-1, LAG-3, CTLA-4, or TIM-3 expression levels in the apheresis and product with response (Fig. S5d, e); differential expression of TIM-3 between apheresis and product suggests upregulation as a result of activation during the manufacturing process. The comparable ratio of total CD8+ to CD4+ cells in responders suggests CD4+ cells may be important to support CD8 function (Fig. S5f).
Collectively, these data illustrate that a TCR T-cell product enriched with activated, EM CD8 cells is associated with response.

Proinflammatory cytokines identified as pharmacodynamic markers associated with response

Post lete-cel infusion, several proinflammatory cytokines were significantly increased in responders as compared with non-responders at Day 3 and 4 (Fig. 3a, b). IFNα, IL-6, and soluble IL-2 receptor alpha (IL-2Ra) were the most robust pharmacodynamic (PD) markers, while granulocyte-macrophage colony-stimulating factor (GM-CSF) and IL-17A were often present at levels below limit of quantification. Expression of these cytokines demonstrates that T cells become activated within a few days post-infusion and this occurs earlier in responders. The increased IFNα in responders is intriguing as it highlights the impact of EM cells in the product which are associated with IFNγ production, and subsequently with response (Fig. 3a, c). The peak expression of soluble IL-2Ra showed the strongest correlation to Cmax, indicating a PK/PD relationship (Fig. 5c). Strong and moderate associations were also observed with GM-CSF and IL-15, respectively (Fig. S6). These robust cytokine data illustrate early activation of T cells in responders. It is encouraging to observe such large differences systemically in a solid tumor setting and suggests changes of the cytokine milieu within the TME.

Lete-cel promotes remodeling of TME by decreasing macrophage levels

While limited tumor biopsies were available in this study (n = 15), gene expression analysis revealed interesting trends. Consistent with previous reports, gene expression and immunohistochemistry (IHC) data indicated that SS tumors were primarily infiltrated by CD163+ and CD68+ macrophages (Fig. S7a, b). Macrophages are associated with poorer prognosis in STS [3-5]. To understand the impact of lete-cel on the TME, we analyzed 10 pre-infusion biopsies and 5 biopsies at progression (d = 34 biologically independent samples). Values are log-transformed for consistency with other cytokine analyses. ANOVA and t-test were performed in c and d to be consistent with remaining cytokine analyses; Kruskal-Wallis p-value = 0.005 for (c) and Wilcoxon p-value = 0.030 for (d). e Impact of transduced cell dose/kg on reduction in tumor size (n = 22 biologically independent samples) for patients in cohorts 1 and 2.

Box plots depict median as horizontal line within box, with box bounds as the first and third quartiles. Dots represent individual data points. Lower whisker is the minimum value of the data within 1.5 times the interquartile range below the 25th percentile. Upper whisker is the maximum value of the data within 1.5 times the interquartile range above the 75th percentile. Two-sided p-values were calculated via bootstrapped median regression (10,000 bootstraps) to adjust for cohort or responder status (a, b), ANOVA (c), t-test (d), and standard test for Spearman correlation (e). CR complete response, IL interleukin, LDR lymphodepleting chemotherapy regimen, PD progressive disease, PR partial response, SD stable disease, SLD sum of longest diameter.

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response in solid tumors have been identified. This comprehensive analysis of 45 SS patients treated with lete-cel identified significant associations between LDR, cell dose, and product attributes with response for the first time. These data demonstrate that LDRs containing fludarabine augment IL-15 levels prior to infusion, which is associated with response. Furthermore, standard LDR together with cell dose/kg increases cell expansion and probability of response. Analysis of the product revealed activated, EM cells were associated with response. Finally, tumor analyses post-infusion illustrated lete-cel infiltration into an immune desert tumor and remodeling of the TME by decreasing macrophage levels. Though data are limited by number of patients and available samples, these findings are intriguing and
suggest directions for cell dose and LDR optimization, balanced composition of product phenotypes, efficacy enhancement technologies, and combinations of therapies to positively impact clinical response. Further work is required and ongoing to validate these observations in a larger set of patients and paired biopsies.

Many of our findings are consistent with observations of CAR T-cell therapy in hematologic malignancies, suggesting similar mechanisms of action. With both cell therapy modalities, peak cell expansion is associated with response. We also report a relationship between cell dose and expansion that has been reported for TCR T-cell therapies but is not well defined for CAR T cells. Our observations align with reports that LDRs containing a combination of cyclophosphamide and fludarabine led to increased CAR T-cell expansion as well as greater increases in IL-15. The association of IL-15 with response supports further exploration of letet-cel in combination with IL-15 agonists. Post-infusion, significant increases in the levels of IFN-γ, IL-6, and GM-CSF were observed in responders, suggesting T-cell activation, in line with previous reports.

The association of infused EM CD8 T cells with response is a unique finding for TCR T-cell therapy. The impact of EM cells has been highlighted in the context of response to checkpoint inhibitors, but only one study has performed a similar characterization of TCR T-cell product. Nagarsheth, et al. found that HPV-16 E7 TCR T-cell product consisted primarily of EM and TEMRA cells, though there was no association with response and the impact of the number of EM cells infused was not evaluated. Several studies have characterized the memory composition of CAR T-cell products and have underscored the role of stem-like and CM cells and/or genes for durable responses in hematologic malignancies. These observations suggest different cell populations may play unique roles for immediate versus durable response and CAR T cells versus TCR T cells. Unlike CAR T cells that recognize cell surface antigens, TCR T cells recognize an antigen presented by an HLA molecule, and therefore depend on HLA for target recognition and activation. Interestingly, although HLA expression on the tumor is low in SS, we observed responses with letet-cel. Based on our findings, we hypothesize that EM cells are necessary to upregulate HLA expression through IFN-γ. EM cells are characterized by higher IFN-γ production than CM or stem-like cells and this is further supported in this study by the correlation of CD8 EM cells to peak IFN-γ post-infusion (Fig. 3d).

Future studies to characterize the TME within a few weeks post-infusion and gene profiling to better define cell populations in the product will be beneficial. Techniques that link gene expression to traditional cell markers will aid in identifying specific populations of interest; current studies use a mixture, which makes comparison across studies difficult. The enrichment of CD8 EM cells in the apheresis of responders and the associations of infused CD8 EM cells with response, Cmax, and peak IFN-γ consistently highlight the importance of this cell type for letet-cel treatment of SS. Further studies are necessary to understand the balance of EM cells, associated with response, and stem-like cells, which may be beneficial for cell persistence.

In terms of mechanisms of resistance, we evaluated antigen loss and T-cell exhaustion. Since the SS patients in this study had high expression of NY-ESO-1 at screening, our data showed no association with response. This may differ in tumor types with more heterogeneous NY-ESO-1 expression, such as non-small-cell lung cancer, gastric, and others. Gene expression analysis revealed no change in NY-ESO-1 expression post-treatment, consistent with previous reports, but a decrease in HLA-A expression and antigen-presenting genes, which may be a mechanism of antigen escape. Nagarsheth et al. reported similar findings of HLA and H2M mutations in tumor biopsies from three patients who showed no response or relapse to treatment with HPV-16 E7 TCR T cells. Loss of heterozygosity of HLA genes has also been reported as a mechanism of immune evasion in treatment with tumor-infiltrating T-cell therapy. Further analysis is needed to determine if the observed downregulation of HLA in this study is due to transcriptional differences, mutations, or copy number variations. If these are transcriptional differences, strategies to maintain upregulation of HLA over time should be considered. For evaluation of exhaustion markers, this study highlighted limitations of bulk gene expression analysis to characterize tumors with few immune infiltrates and pointed to the benefits of single-cell profiling techniques. Collectively, these data provide unique insights into combinations to further enhance responses: for example, therapies that can decrease the myeloid and macrophage components or upregulate antigen presentation.

This study highlighted the benefits of standard LDR and higher cell dose for robust T-cell expansion, identified product attributes associated with response, and showed a trend in tumor remodeling post-T-cell infiltration. Future investigations will include how letet-cel treatment and tumor remodeling may affect the endogenous T-cell repertoire. Our analysis also provided valuable insight into the development of next-generation engineered T-cell technologies, for example data supporting the benefit of CD4 T cells in the product and the high expression of TGF-β in SS tumors. Technologies focused on increasing the persistence of CD4 T cells through co-expression of CDA8a to stabilize the HLA interaction, as well as reducing the inhibitory effect of TGF-β on T cells through a dominant negative receptor.
Fig. 3 | T-cell product enriched with activated, effector memory CD8 cells is associated with response. a Number of CD8+ Pentamer+ cells/kg infused per memory phenotype in non-responders vs responders (n = 36 biologically independent samples). b, c Association of number of infused cells/kg per memory phenotype with peak cell expansion (b) and peak IFNγ post-infusion (c) (n = 34 and 31 biologically independent samples for parts b and c respectively). Associations with EM cells are statistically significant with outlier at lowest infused cell counts removed—EM with Cmax (R = 0.42, p = 0.016) and EM with IFNγ (R = 0.41, p = 0.027). d Association of EM phenotype between apheresis and product (n = 34 biologically independent samples). Box plots depict median as horizontal line within box, with box bounds as the first and third quartiles. Dots represent individual data points. Lower whisker is the minimum value of the data within 1.5 times the interquartile range below the 25th percentile. Upper whisker is the maximum value of the data within 1.5 times the interquartile range above the 75th percentile. Nominal two-sided p-values based on the Wilcoxon rank sum test or log-rank test for PFS are presented and correlations are based on Spearman method. Line of best fit shown in blue for significant associations and gray area represents 95% confidence interval around the regression line. CM central memory (CD45RA-CCR7+), CR complete response, EM effector memory (CD45RA-CCR7−), Naïve (CD45RA+CCR7+), PFS progression-free survival, PD progressive disease, PR partial response, SD stable disease, TEMRA T effector memory RA (CD45RA+CCR7−), TSCM T stem cell memory (CD45RA+CCR7−CD95+CD127+).
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This was a multicenter, open-label, pilot study to determine the efficacy and safety of lete-cel in patients with unresectable, metastatic, or recurrent SS. Study stages included screening, leukapheresis/manufacture, lymphodepletion, and treatment phases, followed by long-term follow-up performed under a separate protocol (Fig. S1). Patient were screened for HLA and NY-ESO-1 and considered enrolled at the time of leukapheresis. The total population enrolled (underwent apheresis) and thus considered for the intent to treatment analysis (ITT) was 50 patients (cohort 1: 15, cohort 2: 14, cohort 3: 5, cohort
A total of five patients dropped out between leukapheresis and T cell infusion. Three patients dropped out due to death (one each from cohort 1, 2, 4), one patient withdrew consent (cohort 1), and one patient withdrew due to disease progression prior to treatment (cohort 1). The modified ITT (mITT) population was 45 patients (cohort 1: 12, cohort 2: 13, cohort 3: 5, cohort 4: 15). The mITT population included 47% (21/45) females and 53% (24/45) males with a median age of 32 years (range of 11–73 years) (Table S1).

Study participants
Inclusion criteria. Patients had to be ≥4 years of age, >18 kg, have Eastern Cooperative Oncology Group (ECOG) performance status of 0–2. Patients could have ≥1 unresectable, locally advanced, or metastatic solid malignancies, including colorectal cancer, prostate cancer, esophageal cancer, melanoma, head/neck squamous cell carcinoma, or nasopharynx cancer. Patients needed to be refractory to or could not tolerate conventional systemic treatment. The study excluded patients with active infections, active autoimmune diseases, history of allergy to any study drug, and pregnant women.
with a minimum 1 × 10⁹ transduced cells and a maximum of 6 × 10⁹ orubicin; NY-ESO-1 positivity, with criteria as detailed for individual a standard chemotherapy regimen containing ifosfamide and/or dox-

diagnosed unresectable or metastatic or progressive/persistent or requirements were: measurable, pathologically, or cytologically-

>3 months, and adequate organ function. Additional eligibility

untreated CNS metastasis; previous treatment with genetically engi-

>1.5 times ULN (isolated bilirubin >1.5 time ULN was acceptable if

转让ase levels >2.5 times the upper limit of the normal range (ULN)

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LME) model. T-cell infusion (TCI) occurred on Day 0. Nominal

infusion and correlation to peak cell expansion. a Nonresponder ratios in cytokine levels over time obtained from linear mixed

Article

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Fig. 5 | Increase in proinflammatory cytokines in responders post lete-cel infusion and correlation to peak cell expansion. a Heatmap of Responder vs Nonresponder ratios in cytokine levels over time obtained from linear mixed models. T-cell infusion (TCI) occurred on Day 0. Nominal p-values from linear effects models were calculated via Wald test and t-distribution and are shown as one dot for 0.01 < p ≤ 0.05 and two dots for p ≤ 0.01. b Time courses of IFNγ, IL-6, IL-17A, and GM-CSF, cytokines differentially upregulated by responders. Geometric means and 95% confidence intervals from LME model (accounting for left-censoring where appropriate) are plotted. Dashed, horizontal lines represented lower limit of quantification. c Time course of soluble IL-2Ra levels showing increase in responders and correlation to peak cell expansion. Line of best fit shown in black and gray area represents 95% confidence bands, both from standard least-squares regression. Sample size varied across timepoints and cytokines, with an overall median of 32 patients (range, 15–38 depending on cytokine/timepoint). For c, Spearman correlation and corresponding two-sided p-value are presented. DY day, GM geometric mean, GM-CSF granulocyte-macrophage colony-stimulating factor, IFN interferon, IL interleukin, WK week.

Exclusion criteria. Patients were excluded if they had alanine amino-

transferase levels >2.5 times the upper limit of the normal range (ULN)

without documented liver metastases/tumor infiltration; total bilirubin

>1.5 times ULN (isolated bilirubin >1.5 time ULN was acceptable if

Figure 5 shows an increase in proinflammatory cytokines in responders post-letercel infusion and correlation to peak cell expansion. A heatmap of responder vs. nonresponder ratios in cytokine levels over time obtained from linear mixed models is provided. T-cell infusion (TCI) occurred on Day 0. Nominal p-values from linear effects models were calculated via Wald test and t-distribution and are shown as one dot for 0.01 < p ≤ 0.05 and two dots for p ≤ 0.01. Time courses of IFNγ, IL-6, IL-17A, and GM-CSF, cytokines differentially upregulated by responders, are shown with geometric means and 95% confidence intervals from LME models (accounting for left-censoring where appropriate). Dashed horizontal lines represent the lower limit of quantification. The time course of soluble IL-2Ra levels showing an increase in responders and correlation to peak cell expansion is also shown, with the line of best fit in black and the gray area representing 95% confidence bands, both from standard least-squares regression. Sample size varied across timepoints and cytokines, with an overall median of 32 patients (range, 15–38 depending on cytokine/timepoint). For this analysis, Spearman correlation and corresponding two-sided p-values are presented. DY day, GM geometric mean, GM-CSF granulocyte-macrophage colony-stimulating factor, IFN interferon, IL interleukin, WK week.

Study endpoints
efficacy. The primary efficacy outcome was investigator-assessed objective response rate (ORR) (complete response or partial response) per Response Evaluation Criteria in Solid Tumors (RECIST) v1.1. This was previously reported for Cohort 1 only by D’Angelo et al.7. Secondary efficacy outcomes included duration of response (DoR), progression-free survival (PFS), best overall response, and overall survival (OS). Best overall response and DoR were previously reported by D’Angelo et al. for Cohort 1 and Ramachandran et al. for all cohorts8. Here we report on safety events across all cohorts, as well as overall response rate as assessed by independent review committee.

Safety. Secondary safety endpoints included adverse events (AEs), serious AEs (SAEs), and AEs of special interest (AESI); all were evaluated using Common Terminology Criteria for Adverse Events v4.0 (CTCAE v4.0). The safety profile of Cohort 1 was previously reported by D’Angelo et al. Here we report on safety events across all cohorts.

Biomarkers. Exploratory biomarker endpoints included correlation of expansion, phenotype, and functionality of lete-cel in the blood and tumor with response to treatment as well as correlation of biomarkers in tumor tissue and blood with response following infusion of lete-cel. The correlation of expansion with response was previously reported by D’Angelo et al. for Cohort 1. The expansion levels per cohort were summarized by Ramachandran et al. for all cohorts. Here we report on additional associations of LDR and cell dose with cell expansion, as well as associations of product attributes, cytokines and tumor gene expression with response.

T-cell expansion and phenotypic analyses

t-cell expansion analysis. Peripheral blood mononuclear cell (PBMC) samples were collected and monitored for expansion of gene-modified cells in patients at baseline (7 days prior to chemotherapy); days 4 and 7; weeks 2, 4, and 8; and months 3, 6, and 12 post-infusion. Thereafter, samples were collected every 3 months until 2 years; every 6 months until 5 years; and then every year until 15 years post-infusion. Total DNA was purified using the QIAamp DNA Blood Mini Kit (Qiagen, Hild, Germany). Presence of the WPRE or Psi transgenes (part of len-

7 ; weeks2 ,4 , and8 ; and months3 ,6 , and12 post-infusion. The thereafter,

cT cells; or a history of active, chronic, or

–cant systemic illness;

–0.01.

–0.05 and two dots for p ≤ 0.01. b Time courses of

– IFN interferon, IL interleukin, WK week.

Study treatment and procedures

Lete-cel manufacture. Autologous T cells were manufactured from

patient derived apheresis at either Cell and Vaccine Production Facility at

the University of Pennsylvania or at Progenitor Cell Therapy. CD25-depleted CD4+ and CD8+ T cells were activated and expanded using αCD3/αCD28 antibody-conjugated beads (Life Technologies) and then used to develop the engineered T cells. T cells were transduced with a self-inactivating lentivirus vector, derived from HIV-1 containing a woodchuck hepatitis virus posttranscriptional regulatory element, at a multiplicity of infection of 1 transducing unit per cell. T cell manufacturing time ranged from 28 to 35 days, including release testing. Transduction potency was measured on primary T cells.

Study procedures. Patients underwent screening assessments,

including collection of blood for HLA typing and IHC evaluation of
tumor for NY-ESO-1 expression, followed by biological sample collection for laboratory assessments, and collection of disease and medical history (Fig. S1). Eligible patients enrolled to the study underwent apheresis. Patients received infectious prophylaxis for Pneumocystis carinii, herpes zoster, and herpes simplex the day prior to commencing lymphodepletion, or as clinically indicated. Prior to lete-cel infusion, patients underwent lymphodepletion dosing as described in Table 1.

On Day 0, patients received thawed lete-cel by intravenous infusion. Patients ≥40 kg received a target dose of 5 × 10⁹ transduced cells, with a minimum 1 × 10⁹ transduced cells and a maximum of 6 × 10⁹ transduced cells. Patients underwent radiologic disease assessments at weeks 4, 8, and 12 every 3 months thereafter, and underwent safety assessments throughout the trial at scheduled timepoints. Patients who progressed are followed for long-term toxicity until death or for up to 15 years post T cell infusion.

Patients could receive a maximum of 2 infusions with lete-cel provided eligibility criteria were met. Patients in any cohort who had a confirmed response or had stable disease for >3 months but then progressed were eligible for a second infusion using the same lymphodepleting regimen as for the first infusion. Patients in Cohorts 3 and 4 who had progressive disease or stable disease as best response for >3 months could receive a second infusion using the high dose of fludarabine and cyclophosphamide lymphodepletion regimen. The second infusion could be given no sooner than 60 days from the first infusion and no later than 2 years after the first infusion.

Study endpoints

Efficacy. The primary efficacy outcome was investigator-assessed objective response rate (ORR) (complete response or partial response) per Response Evaluation Criteria in Solid Tumors (RECIST) v1.1. This was previously reported for Cohort 1 only by D’Angelo et al. Secondary efficacy outcomes included duration of response (DoR), progression-free survival (PFS), best overall response, and overall survival (OS). Best overall response and DoR were previously reported by D’Angelo et al. for Cohort 1 and Ramachandran et al. for all cohorts. Here we report on safety events across all cohorts.

Safety. Secondary safety endpoints included adverse events (AEs), serious AEs (SAEs), and AEs of special interest (AESI); all were evaluated using Common Terminology Criteria for Adverse Events v4.0 (CTCAE v4.0). The safety profile of Cohort 1 was previously reported by D’Angelo et al. Here we report on safety events across all cohorts.

Biomarkers. Exploratory biomarker endpoints included correlation of expansion, phenotype, and functionality of lete-cel in the blood and tumor with response to treatment as well as correlation of biomarkers in tumor tissue and blood with response following infusion of lete-cel. The correlation of expansion with response was previously reported by D’Angelo et al. for Cohort 1. The expansion levels per cohort were summarized by Ramachandran et al. for all cohorts. Here we report on additional associations of LDR and cell dose with cell expansion, as well as associations of product attributes, cytokines and tumor gene expression with response.

T-cell expansion and phenotypic analyses

T-cell expansion analysis. Peripheral blood mononuclear cell (PBMC) samples were collected and monitored for expansion of gene-modified cells in patients at baseline (7 days prior to chemotherapy); days 4 and 7; weeks 2, 4, and 8; and months 3, 6, and 12 post-infusion. Thereafter, samples were collected every 3 months until 2 years; every 6 months until 5 years; and then every year until 15 years post-infusion. Total DNA was purified using the QIAamp DNA Blood Mini Kit (Qiagen, Hillen, Germany). Presence of the WPRE or Psi transgenes (part of lentiviral vector used to transduce the T cells) was measured with custom Taqman probes by quantitative polymerase chain reaction (qPCR) on Viia7 Real Time PCR System (Life Technologies, Waltham, MA). Cell kinetics or expansion was determined by quantifying the DNA copy number based on a standard curve consisting of plasmid DNA containing WPRE and Psi sequences.
**T-cell-phenotypic analysis.** PBMC samples were collected at baseline, 1 week; 1, 2, 6, and 12 months; then every 3 months until 2 years post-infusion; and then every 6 months until 5 years post-infusion. Immunophenotyping was performed on cryopreserved PBMC samples using flow cytometry (Caprion, Montreal, Canada; now part of CellCarta).

Detection reagents and concentrations used for T-cell phenotyping Pheno 1 panel are as follows: Live/Dead Fixable Aqua Stain Kit (ThermoFisher, Catalog#:L34957, Dilution: 1/200 Lot#:2157152), CD3 (Clone: UCHT1, BD Biosciences, Catalog #: 557943, Dilution: 1/100 Lot#: 9050801), CD4 (Clone: RPA-T4, BD Biosciences,Catalog #: 562658, Dilution 1/50 Lot # 8351537), CD8 (Clone:RPA-T8, BD
Biosciences, Catalog #:563821, Dilution 1/800 Lot#: 9073878, CD95 (Clone: DX2, BD Biosciences, Catalog #: 563312, Dilution 1/100 Lot#: 9003850), CCR7 (Clone: G043H7, BioLegend, Catalog #: 353226, Dilution:1/25 Lot#: B238508), CD127 (Clone: A01D5, BioLegend, Catalog #: 353130, Dilution: 1/100 Lot#: B279332), CD45RO (Clone: UCHLI, BD Biosciences, Catalog #: 566067, Dilution 1/100 Lot#: 0310596), CD45RA (Clone: 2H4, Beckman Coulter, Catalog #: IM2711U, Dilution: 1/25 Lot#: 200800), CD25 (Clone: M-A251, BD Biosciences, Catalog #: 557753, Dilution: 1/50 Lot#: 9345728), LAG-3 (Clone: N/A, Cedarlane, Catalog #: FAB2319F, Dilution: 2/25 Lot#: ABCB0417085), TIM-3 (Clone: 3444823, Cedarlane, Catalog #: FAB2565A, Dilution: 1/25 Lot#: ABFB041701), PD-1 (Clone: EH12.2H7, Biologen, Catalog #: 329930, Dilution: 1/50 Lot#: B290009), and NY-ESO-1 Pentamer (H-MA*0201, ProImmune, ProImmune, Catalog #: TP:7712-21). Detection reagents and concentrations used for T-cell phenotyping Pheno 2 panel are as follows: Live/Dead Fixable Aqua Stain Kit (ThermoFisher, Catalog#:L34957. Dilution 1/200 Lot#:2157152), CD3 (Clone: OKT3, Biologen, Catalog #: 317328, Dilution: 1/400 Lot#: B2894294), CD4 (Clone: RPA-T4, Biologen, Catalog #: 300554, Dilution: 1/50 Lot# B309549), CD8 (Clone: RPA-T8, BD Biosciences, Catalog#: 563821, Dilution 1/800 Lot#: 9073878), CD28 (Clone: CD82.2, BD Biosciences, Catalog #: 562976, Dilution: 1/50 Lot#:02665818), CD27 (Clone:0323, Life Technologies, Catalog #: 47-0279-42, Dilution:1/50 Lot#: 2114191), CD103 (Clone: Ber-ACT8, BD Biosciences, Catalog #: 563883, Dilution: 1/200 Lot#:0247897), CD154/CD40L (Clone: TRAP1, BD Biosciences, Catalog #: 562749, Dilution:1/200 Lot#: 9131721, CD134/OX-40 (Clone: ACT35, BD Biosciences, Catalog #: 536663, Dilution: 1/100 Lot#: 0065008, CD137/4-IBB (Clone: 4B-1, BioLegend, Catalog #: 309816, Dilution: 2/25 Lot#: B2920000), CT152/CTLA4 (Clone: BNI3, BD Biosciences, Catalog #: 562743, Dilution: 1/50 Lot#: 0030269), CD274/PD-1 (Clone: MH1, BD Biosciences, Catalog #: SS8065, Dilution: 2/25 Lot#:9143730), and NY-ESO-1 Pentamer (HLA-A*0201, ProImmune, ProImmune, Catalog #: TP:7712-21). See more details in Table S7. PBMCs were thawed (1 x 10^6 cells/panel) and incubated with Fc blocker (for Pheno2 only) for 10 min at room temperature, prior to being washed and subjected to pentamer staining (10 min at room temperature). PBMCs were then washed and stained with surface stain (30 min at 4 °C), then washed again and fixed in 0.5% paraformaldehyde (30 min at 4 °C). Cells were then washed again before acquisition. Data was acquired on LSR II flow cytometer (BD Biosciences) and analyzed using Flowjo software (BD). Gating strategy is shown in Fig. S9. Hierarchical gating was used for all markers except stem-cell memory cells, which used Boolean gating (CD45RA + CCR7 + CD45RO-CD95 + CD127+).

Serum cytokine analysis

Concentration of serum cytokines was measured at baseline; day 0 pre-infusion; 1, 4, and 7 days post-infusion; and 2, 3, 4, 6, and 8 weeks post-infusion by the Mesoscope Discovery (MSD) immunoassay at Cambridge Biomedical (Boston, MA: now part of BioAgilityx). Three commercially available kits (V-PLEX Proinflammatory Panel 1; V-PLEX Cytokine Panel 1 and U-PLEX Biomarker Group 1) were used to collectively analyze the cytokine profiles of GS-CSF, IFN-γ, IL1α, IL1β, IL-1α, IL-2, IL-2Ra, IL-4, IL-5, IL-6, IL-7, IL-8, IL-10, IL-12/IL-23p40, IL-12p70, IL-13, IL-15, IL-16, IL-17A, TNF-α, TNF-β and VEGF-A. Data was collected using the MESO QuickPlex SQ20 (MSD).

Analyses of tumor biopsies

RNA analysis. RNA analysis was performed by Histogenex (Wilrijk, Belgium; now part of CellCarta). For each sample, five 4-μm unstained slides were used for macrodissection and subsequent RNA extraction. RNA extract was quantified (including assessment of RNA purity) using the Quant-it RiboGreen RNA Reagent and Kit, and RNA quality was assessed using Agilent RNA Pico chip analysis.

RNA was analyzed using the NanoString nCounter® system, with 2 sets of NanoString assays (nCounter® PanCancer Immune Profiling Panel and nCounter® PanCancer Pathway Panel) run on the same extract. The normalization for raw nCounter counts of expressed genes is separately done for QC-passed samples in PanCancer immune and PanCancer pathway panel using the R-package NanoStringNorm (R version 4.0.3) with a set of parameters: CodeCount = ‘geo.mean’, Background = ‘mean-5sd’, SampleContent = ‘housekeeping.geo.mean’, round.values = TRUE, take.log = TRUE.

Detection of TCR T cells by RNA in situ hybridization. RNA in situ hybridization on biopsied tissues was performed using the NanoScope® 2.5 HD Duplex Reagent Kit (Advanced Cell Diagnostics, Newark, CA) comprising TCR T cell and CD3 mRNA detection assays. 5-μm formalin-fixed, paraffin-embedded (FFPE) tissue sections were pretreated with heat and protease prior to hybridization with the target oligo probes. Preamplifier, amplifier, and horseradish peroxidase/alkaline phosphatase-labeled oligos were then hybridized sequentially, followed by chromogenic precipitate development.

Each sample was quality controlled for RNA integrity with an NanoScope® probe specific to PB2/POLR2A RNA and for background with a probe specific to bacterial dapB RNA. The NanoScope® CD3 probe comprised a pool of three human CD3 antigens (CD3d, CD3e, and CD3g, Advanced Cell Diagnostics, Catalog #: 426628) and the TCR probe comprised a pool of two human TCR α and β chain mRNA detection assays. The RNAscope® 2.5 HD Duplex Reagent Kit (Advanced Cell Diagnostics, Catalog #: 2.5 HD Duplex Reagent Kit) was used as a negative control for bacterial dapB RNA.

Detection of TCR T cells by RNA in situ hybridization. RNA in situ hybridization on biopsied tissues was performed using the NanoScope® 2.5 HD Duplex Reagent Kit (Advanced Cell Diagnostics, Newark, CA) comprising TCR T cell and CD3 mRNA detection assays. 5-μm formalin-fixed, paraffin-embedded (FFPE) tissue sections were pretreated with heat and protease prior to hybridization with the target oligo probes. Preamplifier, amplifier, and horseradish peroxidase/alkaline phosphatase-labeled oligos were then hybridized sequentially, followed by chromogenic precipitate development.

Each sample was quality controlled for RNA integrity with an NanoScope® probe specific to PB2/POLR2A RNA and for background with a probe specific to bacterial dapB RNA. The NanoScope® CD3 probe comprised a pool of three human CD3 antigens (CD3d, CD3e, and CD3g, Advanced Cell Diagnostics, Catalog #: 426628) mRNA, whereas the TCR probe was custom-made. Specific RNA staining signal was identified as green or red punctate dots. Samples were counterstained with hematoxylin. Representative images were digitally obtained using CaseViewer (3D Histech, Budapest, Hungary).

Protein expression by IHC. NY-ESO-1 staining was performed using the E978 clone (Sigma, Catalog #: N2038, at 1 μg/mL) at QuatTek Laboratory (Goleta, CA; now part of Discovery Life Sciences). The following markers were analyzed at Histogenex (Wilrijk, Belgium; now part of CellCarta) by IHC (all analyzed using Ventana BenchMark XT unless noted otherwise): CD4 (clone SP35, Ventana, Catalog #: 790-4423, no dilution), CD8 (clone C8/144B, Dako, Catalog #: M7103, 1/75 dilution), CD20 (clone L26, Ventana, Catalog #: 760–2321, no dilution), CD45 (clone 2B11 + PD7/26, Agilent; catalog #: M70101L, 1/100 dilution, staining on autostainer), CD163 (clone MRQ-26, Ventana, Catalog #: 760–4437, no dilution), LAG-3 (clone 17B4, Novus biologicals, catalog #: 97657, 1/2000 dilution), Pan Keratin (clone AE1/AE3/PCK16, Ventana, Catalog #: 760–2595, no lymphodepletion). At progression, samples consist of five samples. Box plots depict median as horizontal line within box, with box bounds as the first and third quartiles. Dots represent individual data points. Lower whisker is the minimum value of the data within 1.5 times the interquartile range below the 25th percentile. Upper whisker is the maximum value of the data within 1.5 times the interquartile range above the 75th percentile. Heatmap show z-scores per gene. Nominal two-sided p-values obtained from linear mixed effects models (a), limma models (e), and standard test for Spearman correlation coefficient (e). IFN interferon, IHC immunohistochemistry, NR non-responder, R responder.
(dilution), PD-1/CD279 (clone SP269, Abcam, catalog #: GR3208557-2, 1/50 dilution), PD-L1 (clone SP142, Ventana, catalog #: M4424, 1/250 dilution), and TIM-3 (clone D5D5R, Cell Signaling Technologies, catalog #: 45208, 1/250 dilution). Representative images were digitally obtained using CaseViewer (3D Histech, Budapest, Hungary).

**Statistical analysis**

**Populations for analysis.** The intent-to-treat (ITT) population included all enrolled patients, whereas the modified ITT (mITT) population, used for safety and efficacy assessments, included patients who received lete-cel infusion. The population for biomarker analyses included patients who received lete-cel infusion with available...
b) Additional validation of the antigen-presenting ability of the mITT population for the primary endpoint was done by comparing 6-8 biologically independent samples to the expansion correlates cohort. 

evaluation of expansion correlates. Post-hoc relationships between cell expansion, biomarker expression, and efficacy were evaluated in a hypothesis-driven manner using Wilcoxon, logistic, linear, and median regression (R version 3.5.1), after log-transforming data when appropriate.

Cytokine analysis. Cytokine analysis was based on a linear mixed effects model, log-transformed cytokine level modeled with treatment x time interactions and a random subject intercept (with otherwise independent errors). For cytokines having ≤1 left-censored (below lower limit of quantification) value, the R-package lim4 (version 1.1–23) was used. For cytokines having ≥2 left-censored values, left censoring was addressed using the R-package lim4 (version 1.0). In all cases Kenward & Roger’s degrees of freedom were used, calculated for lim4 models using the R-package pbkrtest (version 0.4–8.6). Continuous AR1 models were also fit for cytokines having ≤1 left-censored value; although they often resulted in better BIC values, they did not change substantive conclusions. As lim4 does not support continuous AR1 models, independence models were kept for all cytokines. Analyses were conducted in R version 4.0.2.

RNA analysis. For RNA analysis, both gene-level and gene-set analyses were conducted for Nanostring data, with each of the two panels fit separately. ORR comparisons were based on limma models58 and implemented via the limma R/Bioconductor package (version 3.44.3), with log2-expression as response and ORR as a single covariate. Pre-treatment versus At-Progression comparisons were conducted using linear mixed effects models (lim4, version 1.1–23) to address repeated measures. PFS comparisons were based on Cox proportional hazards models with PFS as response and log2-expression as a single covariate. To summarize differential expression across gene sets, global significance statistics were based on t-statistics from each gene within a set of interest (\(\sum t_i^2\)). Corresponding p-values were obtained by permutation test (5000 permutations). Similarly, Competitive Fisher test odds ratios were based on cross-tabulation of gene set membership with nominal significance (p < 0.05); p-values were obtained by permutation test using Fisher Exact test p-value as objective function. Gene sets were obtained by selecting collections from KEGG (all HSA sets), GO (immune and cellular communication processes), REACTOME (all HSA sets), MsigDB (C4, C6, and Hallmarks), and a few other hand-curated sets obtained from Nanostring files or literature review60,61; only gene sets with ≥5 overlapping non-constant genes and ≥50% coverage of the original gene set on the respective panel were considered. Analyses were conducted in R version 4.0.2.

Reporting summary
Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability
For reasons of privacy protection for study participants, GSK offers access to data and materials via controlled access. Anonymized individual participant data from this study plus the annotated case report form, protocol, reporting and analysis plan, dataset specifications, raw downstream statistical analyses were based on the Wilcoxon rank sum test, whereas correlations were based on Spearman correlation coefficients.
code availability

Quantification and statistical analyses for all data types was conducted using publicly available packages in R.

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