Gene-edited healthy donor CAR T cells show superior anti-tumour activity compared to CAR T cells derived from patients with lymphoma in an in vivo model of high-grade lymphoma

Article (Accepted Version)

Title: Gene edited healthy donor CAR T cells show superior anti-tumour activity compared to CAR T cells derived from patients with lymphoma in an *in vivo* model of high grade lymphoma

Running title: Comparison of healthy donor and lymphoma CAR T cells

Corresponding author: Charlotte Elizabeth Graham, King's College London, Faculty of Life Sciences and Medicine, School of Cancer and Pharmaceutical Sciences, 123 Coldharbour Lane, SE5 9NT. Email: charlotte.e.graham@kcl.ac.uk, Tel: 07843061403

Agnieszka Jozwik, King's College London

Ruby Quartey-Papafio, King's College London

Nikolaos Ioannou, King's College London

Ana M Metelo, King's College London

Carlo Scala, King's College London

Glenda Dickson, King's College London

Orla Stewart, King's College Hospital NHS Foundation Trust

Maria Almena-Carrasco, Institut de Recherches Internationales Servier, Paris, France

Elisa Peranzoni, Institut de Recherches Internationales Servier, Paris, France

Alan G Ramsay, King's College London

Piers EM Patten, King's College London and King's College Hospital NHS Foundation Trust

Thomas Pertel, Allogene Therapeutics

Farzin Farzaneh, King's College London

Sandra Dupouy, Institut de Recherches Internationales Servier, Paris, France

Andrea Pepper, University of Sussex, Brighton and Sussex Medical School

Reuben Benjamin, King's College London and King's College Hospital NHS Foundation Trust

Competing Interests statement:

Research funding for this project was provided by Servier. Maria Almena-Carrasco, Elisa Peranzoni and Sandra Dupouy are employees of Servier. Thomas Pertel is an employee of Allogene therapeutics which develops allogeneic CAR T cells.

CD19-targeted autologous chimeric antigen receptor (CAR) T cell therapy has shown dramatic response rates in relapsed and refractory patients with B cell malignancies (1–4). However, a growing body of literature has demonstrated T cell dysfunction in some cancer patients which impairs the effectiveness of the end CAR T cell product (5–7). Healthy donor (HD) CAR T cells could potentially provide a source of more functional cells. Graft versus host disease (GvHD) limits the use of non HLA matched HD CAR T cells, but gene-editing to remove the native alpha beta T cell receptor (TCR) from HD CAR T cells has allowed HD TCR^- CAR T cells to be given to HLA unmatched patients with B-acute lymphoblastic leukaemia (B-ALL) or with B cell lymphoma in clinical trials(8–10).

This study sought to compare the functionality of HD and HD TCR^- CAR T cells with B cell lymphoma patient CAR T cells. *In vitro* functional assays were performed and *in vivo* activity was assessed using a xenograft model of high grade B cell lymphoma (NOD/SCID/IL2Rγ^{null}(NSG) Raji luciferase), correlating efficacy with phenotypic features of the CAR T cell product.

Peripheral blood mononuclear cells (PBMCs) were collected from consenting B cell lymphoma patients (n=7) who underwent apheresis for a commercial CAR T cell product, and from young adult HDs (age 18-30 years, n=13) (Human Tissue Authority Licence number 12223 and King's College London Research Ethics Committee Ref: HR-17/18-5515). Young adults were chosen because aged T cells are thought to be more terminally differentiated with reduced proliferative capacity(11). Using the same CAR construct (anti-CD19 4G7 scFv 4-1BB CD3ζ lentiviral CAR) (figure 1a) and manufacturing process, research grade lymphoma patient and HD CAR T cells were produced. HD TCR^- CAR T cells were made by electroporating HD CAR T cells with TALEN® mRNA targeting the

TRAC locus (T cell receptor alpha constant). Residual unedited CAR T cells were removed by magnetic bead depletion(12). Manufacturing lasted 14 days for all CAR T cell groups prior to cryopreservation and storage.

Lymphoma patients were older (median age 52, range 30-73 years) than HDs, and met eligibility criteria for a commercial anti-CD19 CAR T cell product. They had received a median of 3 lines of therapy (range 2-5, Table 1 supplementary). 3/7 had a prior autologous haematopoietic stem cell transplant (HSCT) and 1/7 had a prior allogeneic HSCT. One of 7 patients had primary mediastinal B cell lymphoma (PMBCL), 3/7 had diffuse large B cell lymphoma (DLBCL), and 3/7 had transformed follicular lymphoma (tFL). These patients included both subsequent responders and non-responders (NR) to a commercial CAR T product (Table 1 supplementary).

Flow cytometry of thawed CAR T cells showed that HD (n=13) and HD TCR^- (n=10) CAR T cells had a higher proportion of naïve and central memory $CD8^+$ CAR T cells than lymphoma CAR T cells (n=6) (figure 1b), and a higher proportion of $CD8^+CD27^+PD\text{-}1^-$ CAR T cells (HD mean 21.53% vs lymphoma mean 5.733%, p=0.0464; HD TCR^- mean 26.56% vs lymphoma mean 5.733%, p=0.0103, one way ANOVA p=0.0182, with Tukey's multiple comparisons test for paired comparisons) (figure 1c). Lymphoma $CD8^+$ CAR T cells more frequently co-expressed PD-1 and TIM3, than HD $CD8^+$ CAR T cells (supplementary figure) and had a higher proportion of triple positive $CD8^+$CAR T cells expressing PD-1, TIM3 and LAG3 than HD CAR T cells (p=0.039) (Figure 1e). However, when comparing gene edited HD TCR^- CAR T cells with lymphoma CAR T cells this difference did not reach statistical significance. Lymphoma CAR T cells had a higher CD4:CD8 ratio than HD TCR^- CAR T cells (supplementary data). *In vitro* activation assays showed lymphoma CAR T cells

had higher baseline expression of the early activation marker CD69, and less antigen specific activation upon stimulation with the $CD19^+$ NALM-6 cell line (figure 1d) which may suggest more differentiated CAR T cells at risk of exhaustion. However, upregulation of CD25, a late activation marker was comparable in all groups (supplementary data). In 24 hour *in vitro* cytotoxicity assays HD, HD TCR^- and lymphoma CAR T cells showed similar killing capacity against NALM-6 and Raji $CD19^+$ cell lines (figure 1 f-g). IFN-γ secretion was demonstrated in co-culture of CAR T cells with NALM-6 and was comparable between CAR T groups (figure 1h).

An *in vivo* CAR T cell 'stress test' was performed to see if there were differences in potency between CAR T cell products not identified by *in vitro* assays(13). A subtherapeutic dose of CAR T cells was given to Raji luciferase bearing NSG mice, allowing tumour escape to occur and thereby challenging the CAR T cell product. NSG mice were injected *via* the tail vein with 1 x 10^5 Raji luciferase cells. Five days later, once tumour engraftment was established, mice were injected i.v. with 5 x 10^5 CAR^+ T cells from HD (n=6), HD TCR^- (n=3) or B-cell lymphoma (n=5) CAR T cell products. Untransduced T (UT) cells were used as a negative control (figure 2a). Cell products from each donor or patient were tested in groups of 3-5 mice (HD n=27, HD TCR^- n=13 and lymphoma n=20 mice). Mice were monitored daily for signs of distress by technicians who were not aware of the CAR T group assignment. Tumour growth was assessed twice weekly with bioluminescence imaging (BLI), following intraperitoneal luciferin injection. Mice were euthanised when they developed signs of distress persisting for > 48 hours such as being hunched, or immediately if they developed difficulty moving or breathing.

Flux data demonstrated rapid tumour growth in mice treated with UT cells until day 9 post T cell injection, after which bioluminescence signal became saturated. Tumour growth was slower in CAR T-treated mice. There was more effective tumour control in HD and HD TCR^- CAR T treated mice than in lymphoma CAR T-treated mice (day 9 flux HD CAR vs lymphoma CAR p=0.036, HD TCR^- CAR vs lymphoma CAR p=0.0365, one way ANOVA p=<0.0001 with Tukey's multiple comparisons test for paired analysis) (figure 2b).

UT mice survived a median of 14 days (range 12-15 days) post T cell injection. Survival was increased in all CAR T cell groups. However, survival was longer in HD (median 19 days, range 13-72 days) and HD TCR^- (median 20 days, range 14-27) CAR T-treated mice compared to the lymphoma CAR T group (median 15 days, range 13-29) (log rank test, HD vs lymphoma CAR T p=0.0076, HD TCR^- vs lymphoma p=0.0859) (figure 2c). In paired analysis of HD and HD TCR^- CAR T cells from the same healthy donors (n=3), each tested in 3-5 mice, no difference was seen in survival (HD median survival 20 days, range 13-27, HD TCR^- median survival 20 days, range 14-27 days), suggesting that gene-editing to remove TCR expression did not impair T cell function.

HD CAR T cell products could potentially allow the selection of 'good performers', thus increasing the functional advantage seen with HD CAR T cells. Differences were seen in performance between individual lymphoma patient and HD derived CAR T cell products. In order to identify the characteristics of a superior CAR T cell product, we correlated median survival with CAR T cell phenotypes (Spearman's correlation). There was no correlation with the proportions of $CD45RO^-CCR7^+$ naïve and stem cell memory, $CD45RO^+CCR7^+$ central memory, $CD45RO^+CCR7^-$ effector memory, or $CD45RO^-CCR7^-$ terminal effector CAR T cells, on either CD4 or CD8 CAR T cells. Similarly, there was no correlation with

percentage of CD8 or CD4 CAR^+ T cells expressing PD-1, LAG3 or TIM3. However, the percentage of CAR T cells which were $CD8^+CD27^+PD\text{-}1^-$, thought to represent naïve, stem cell memory and central memory populations(5), significantly correlated with median survival (Spearman r= 0.7762, p=0.0016) (Figure 2d).

It has been shown that product related T cell characteristics influence clinical outcome, for example in CLL the proportion of a specific memory population ($CD8^+CD27^+PD\text{-}1^-$) correlated with remission status(5) and in B Cell lymphoma $CD8^+CCR7^+CD27^+$ cells were three times higher in the infusion product from patients who achieved a CR compared to those who did not(14). We found a higher proportion of this $CD8^+CD27^+PD\text{-}1^-$ population in HD and HD TCR^- CAR T cells compared with lymphoma CAR T cells. Although, the functionality of this population has only been reported in CLL, a recent paper which examined single cell transcriptomics and clonal evolution of CAR T cells found a preferential expansion of $CAR^+CD8^+CD27^+$ clones infused into lymphoma patients, using a different CAR construct and manufacturing process(15). Furthermore, Fraietta et al demonstrated that removal of CAR^+ $CD8^+CD27^+PD\text{-}1^-$ T cells resulted in loss of tumour control in the NALM-6 NSG xenograft model(5). Using a different tumour model, CAR construct and T cell donor source, we have shown that the proportion of $CAR^+CD8^+CD27^+PD\text{-}1^-$ cells from HDs and lymphoma patients correlated with median survival of mice in a Raji NSG xenograft model, thus underlining the significance of this population. 4/6 lymphoma patients, tested in our model, achieved a CR at 1 month post infusion, and in this group there was a trend towards a higher proportion of $CAR^+CD8^+CD27^+PD\text{-}1^-$ T cells (mean 7.435% versus 2.735% in NR patients), but the numbers were too small to draw conclusions, furthermore at 3 months only one patient remained in CR.

We did not specifically select HDs with a high percentage of $CAR^+CD8^+CD27^+PD\text{-}1^-$ T cells. However, an 'off the shelf' HD TCR^- CAR T cell product would enable screening for products with a high proportion of this population. The HDs in this study were all young adults. It is not known whether the inferior performance of autologous CAR T cells derived from lymphoma patients was the result of T cell senescence, prior therapies or tumour induced dysfunction. It is therefore not possible to determine from our data whether younger lymphoma patients and those who have received fewer lines of therapy would also have an inferior CAR T product compared to HD CAR T cells. The use of age matched controls and untreated lymphoma patients would provide data unaffected by cell senescence or treatment induced dysfunction, but our comparison is clinically relevant and representative of lymphoma patients currently accessing commercial CAR T cell products.

Other groups have shown superior function of HD CAR T cells compared to patient derived CAR T cells *in vivo*(5,6), but these HD CAR T products were not suitable for treating patients due to the risk of GvHD. This study has shown for the first time in a pre-clinical model the superior functionality of a HD TCR^- CAR T cell product compared to lymphoma patient derived CAR T cells. Further work is needed to identify the optimal donor for an 'off the shelf' allogeneic product. In order to maximise the therapeutic benefit of HD TCR^- CAR T cells, host rejection of non HLA matched CAR T cells would need to be safely overcome.

Acknowledgements

This research was supported by the National Institute for Health Research (NIHR) Biomedical Research Centre based at Guy's and St Thomas' NHS Foundation Trust and King's College London. The views expressed are those of the authors and not necessarily those of the NHS, the NIHR or the Department of Health and Social Care. Research funding

was provided by Servier. Allogeneic CAR-T cell products targeting CD19 gene-edited by TALEN® are exclusively licensed to Servier from Cellectis and use Cellectis' technologies.

Competing Interests

Servier provided research funding for this study. Maria Almena-Carrasco, Elisa Peranzoni and Sandra Dupouy are employees of Servier. Thomas Pertel is an employee of Allogene therapeutics.

References

1. Neelapu SS, Locke FL, Bartlett NL, Lekakis LJ, Miklos DB, Jacobson CA, et al. Axicabtagene ciloleucel CAR T-cell therapy in refractory large B-Cell lymphoma. New England Journal of Medicine. 2017;
2. Maude SL, Laetsch TW, Buechner J, Rives S, Boyer M, Bittencourt H, et al. Tisagenlecleucel in children and young adults with B-cell lymphoblastic leukemia. New England Journal of Medicine. 2018;
3. Schuster SJ, Bishop MR, Tam CS, Waller EK, Borchmann P, McGuirk JP, et al. Tisagenlecleucel in adult relapsed or refractory diffuse large B-cell lymphoma. New England Journal of Medicine. 2019;
4. Brentjens RJ, Davila ML, Riviere I, Park J, Wang X, Cowell LG, et al. CD19-targeted T cells rapidly induce molecular remissions in adults with chemotherapy-refractory acute lymphoblastic leukemia. Science Translational Medicine. 2013;
5. Fraietta JA, Lacey SF, Orlando EJ, Pruteanu-malinici I, Gohil M, Lundh S, et al. Determinants of Response and Resistance to CD19 CAR T Cell Therapy of CLL. Nature Medicine. 2018;
6. Arcangeli S, Falcone L, Camisa B, De Girardi F, Biondi M, Giglio F, et al. Next-Generation Manufacturing Protocols Enriching TSCM CAR T Cells Can Overcome Disease-Specific T Cell Defects in Cancer Patients. Frontiers in Immunology. 2020;
7. Das RK, Vernau L, Grupp SA, Barrett DM. Naïve T-cell deficits at diagnosis and after chemotherapy impair cell therapy potential in pediatric cancers. Cancer Discovery. 2019;
8. Benjamin R, Graham C, Yallop D, Jozwik A, Mirci-Danicar OC, Lucchini G, et al. Genome-edited, donor-derived allogeneic anti-CD19 chimeric antigen receptor T cells in paediatric and adult B-cell acute lymphoblastic leukaemia: results of two phase 1 studies. The Lancet. 2020 Dec 12;396(10266):1885–94.
9. Neelapu SS, Munoz J, Locke FL, Miklos DB, Brown R, McDevitt JT, et al. First-in-human data of ALLO-501 and ALLO-647 in relapsed/refractory large B-cell or follicular lymphoma (R/R LBCL/FL): ALPHA study. Journal of Clinical Oncology. 2020;
10. Jacobson CA, Herrera AF, Budde LE, DeAngelo DJ, Heery C, Stein A, et al. Initial Findings of the Phase 1 Trial of PBCAR0191, a CD19 Targeted Allogeneic CAR-T Cell Therapy. Blood. 2019;
11. Miller RA. The aging immune system: Primer and prospectus. Science. 1996;
12. Poirot L, Philip B, Schiffer-Mannioui C, Le Clerre D, Chion-Sotinel I, Derniame S, et al. Multiplex genome edited T-cell manufacturing platform for "off-the-shelf" adoptive T-cell immunotherapies. Cancer Research. 2015;
13. Zhao Z, Condomines M, van der Stegen SJC, Perna F, Kloss CC, Gunset G, et al. Structural Design of Engineered Costimulation Determines Tumor Rejection Kinetics and Persistence of CAR T Cells. Cancer Cell. 2015;
14. Deng Q, Han G, Puebla-Osorio N, Chun John Ma M, Strati P, Chasen B, et al. Characteristics of anti-CD19 CAR T cell infusion products associated with efficacy and toxicity in patients with large B cell lymphomas. Nature Medicine. 2020;26:1878–87.
15. Sheih A, Voillet V, Hanafi LA, DeBerg HA, Yajima M, Hawkins R, et al. Clonal kinetics and single-cell transcriptional profiling of CAR-T cells in patients undergoing CD19 CAR-T immunotherapy. Nature Communications. 2020;

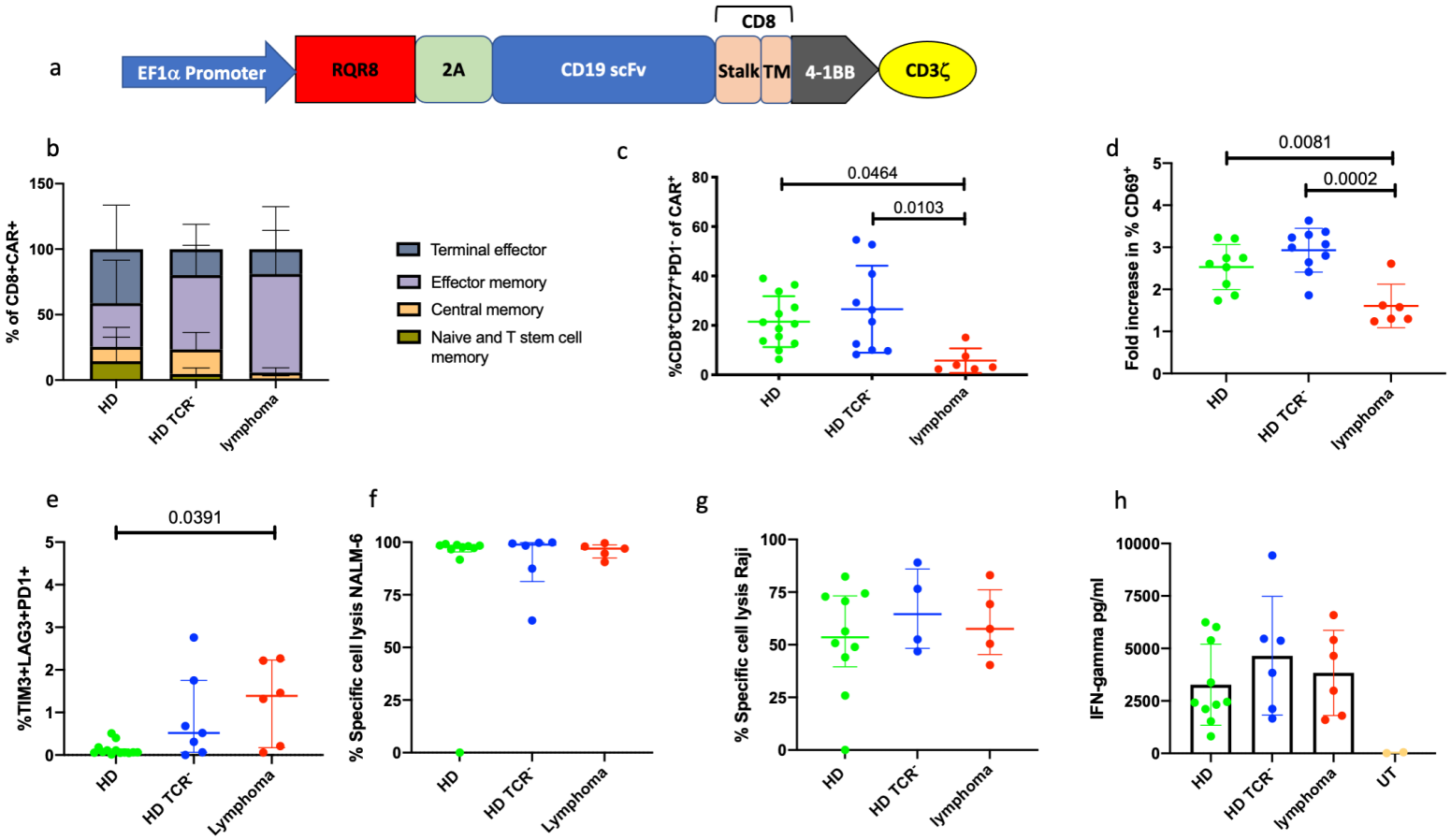
236
237

Figure Legends:

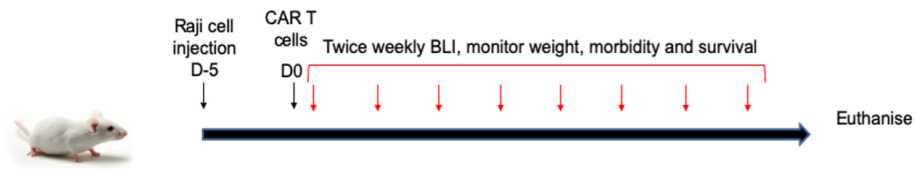
Figure 1 a) Schematic diagram of CAR construct. b) Memory subsets on $CD8^+CAR^+$ cells are shown. Naïve and stem cell memory ($CD45RO^-CCR7^+$), central memory ($CD45RO^+CCR7^+$), effector memory ($CD45RO^+CCR7^-$), terminal effector ($CD45RO^-CCR7^-$). Mean and standard deviation are displayed. c) Percentage of $CD8^+CD27^+PD\text{-}1^-$ cells are displayed for the different CAR T groups. They are seen at a higher proportion in HD and HD TCR^- CAR T cells than with lymphoma CAR T cells. Mean with standard deviation (SD) displayed, one-way ANOVA p=0.0182, adjusted p-values for paired comparisons using Tukey's multiple comparisons test. d) Fold increase in CD69 is significantly higher on HD and HD TCR^- CAR T cells compared to lymphoma CAR T cells when stimulated with NALM-6 cells in a 1: 1 ratio for 24 hours (mean with SD) One-way ANOVA p=0.0003, adjusted p-values for paired comparisons displayed using Tukey's multiple comparisons test. e) Percentage of $CD8^+$ CAR T cells triple positive for PD-1, LAG3 and TIM-3 is displayed (Kruskal Wallis p=0.0277, with adjusted p-values displayed using Dunn's multiple comparisons test). f) CAR T or UT cells were cultured with GFP^+ NALM-6 or g) GFP^+ Raji cells in a 1:1 ratio for 24 hours and the percentage of specific cell lysis following 24 hours co-culture is shown (median with interquartile range)(specific cell lysis= (% viable with UT-% viable with CAR T cells)/% viable with UT) x100, all CAR T groups showed superior killing to UT cells. h) IFNγ secretion as measured by Luminex platform in supernatant harvested from 24 hours co-culture with NALM-6 cell line. IFNγ values are shown after removing the baseline values (cytokine secretion from CAR T cells cultured alone) from individual samples. All CAR T groups showed increased IFNγ production compared to UT cells (mean with SD).

Figure 2 a) Schematic diagram of *in vivo* experiment design with Raji xenograft model. Mice are injected i.v. with 1 x 10^5 Raji luciferase cells on day -5, on day 0 they are injected i.v.

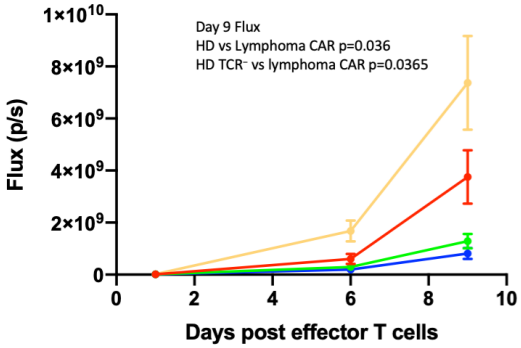
with 5 x 10^5 CAR^+ T cells. Tumour growth is monitored twice weekly with BLI following IP injection of luciferin. b) Raji cell growth is faster in lymphoma CAR T treated mice compared to HD and HD TCR^- CAR T treated mice. Mean flux and standard error margin is shown for each treatment group with data pooled from 2 experiments. Day 9 flux HD CAR vs lymphoma CAR p=0.036, HD TCR^- CAR vs lymphoma CAR p=0.0365, one way ANOVA p=<0.0001 with Tukey's multiple comparisons test for paired analysis c) Survival curves demonstrate improved survival in HD compared to lymphoma CAR T treated mice (p=0.0076, log rank test), but comparable survival between HD and HD TCR^- CAR T treated mice. d) Median overall survival of mice correlated with the proportion of pre-infusion CAR T cells which were $CD8^+CD27^+PD\text{-}1^-$ (Spearman r=0.7762, p=0.0016) (n=6 HD, n=3 HD TCR^- and n=5 Lymphoma CAR T products, each tested in 3-5 mice e.g n=27 HD, n=13 HD TCR^- and n=20 Lymphoma treated mice). e) Mice were weighed twice a week during the experiment and results are plotted against time.


a
EF1α Promoter
RQR8
2A
CD19 scFv
CD8
Stalk
TM
4-1BB
CD3ζ
b
% of CD8+CAR+
150
100
50
0
HD
HD TCR-
lymphoma
Terminal effector
Effector memory
Central memory
Naive and T stem cell memory
c
%CD8+CD27+PD1- of CAR+
80
60
40
20
0
0.0464
0.0103
HD
HD TCR-
lymphoma
d
Fold increase in % CD69+
5
4
3
2
1
0
0.0081
0.0002
HD
HD TCR-
lymphoma
e
%TIM3+LAG3+PD1+
5
4
3
2
1
0
0.0391
HD
HD TCR-
Lymphoma
f
% Specific cell lysis NALM-6
100
75
50
25
0
HD
HD TCR-
Lymphoma
g
% Specific cell lysis Raji
100
75
50
25
0
HD
HD TCR-
lymphoma
h
IFN-gamma pg/ml
10000
7500
5000
2500
0
HD
HD TCR-
lymphoma
UT

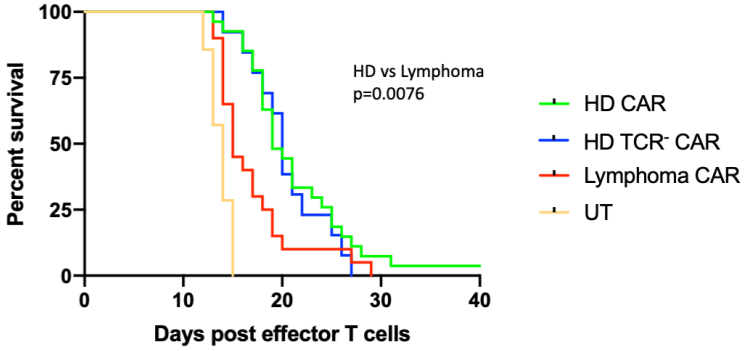
a



b



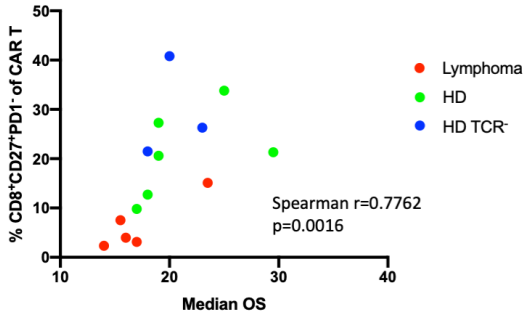
c



Numbers at risk:

Day	0	5	10	15	20	25	30	35	40
HD CAR	27	27	27	26	13	7	2	1	1
HD TCR- CAR	13	13	13	13	8	3	0	0	0
Lymphoma	20	20	20	13	2	2	0	0	0
UT	7	7	7	2	0	0	0	0	0

d



e