

RETRACTED ARTICLE: JAK-STAT Domain Enhanced MUC1-CAR-T Cells Induced Esophageal Cancer Elimination

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Purpose: Chimeric antigen receptor (CAR)-T cells have shown to play a vital role in anti-tumor functions in hematological malignancies, but have poor efficacy in solid tumors. To improve the activation and proliferation of CAR-T cell in solid tumors, we constructed an enhanced CAR-T cells to increase the survival of esophageal cancer.

Materials and Methods: To construct enhanced CAR-T cells, we chose MUC1 as the target of CAR-T cells. Long-term co-culture of target cells and effector cells was applied to verify the antitumor activity of the enhanced MUC1-CAR-T cells in vitro. Moreover, a mouse xenograft model was established to investigate the effects of enhanced MUC1-CAR-T cells on tumor elimination in vivo.

Results: In vitro studies showed that enhanced MUC1-CAR-T cells have long-lasting tumor killing and proliferative capabilities. Moreover, animal experiments verified that enhanced MUC1-CAR-T cells had significant anti-tumor function and a prolonged half-life by subcutaneous transplantation models of esophageal cancer and PDX models of esophageal cancer, in vivo.

Conclusion: These results indicated that enhanced MUC1-CAR-T cells have a significant cytotoxic effect on esophageal cancer, and may likely to provide a novel strategy for the treatment of esophageal cancer.

Keywords: JAK-STAT, MUC1, esophageal cancer, chimeric antigen receptor-T cells, CAR-T cell

Background

Esophageal cancer (EC) is one of the most common malignancies in China, and the main histological category is esophageal squamous cell carcinoma (ESCC).¹ Although esophagostomy is the most effective treatment for ESCC patients at present, the long-term survival is quite low and unsatisfactory with a relative overall five-year relative survival rate of only 20–30%.² In addition, more than half of all postoperative patients relapse within 2–3 years, among which almost 80% eventually die due to cancer recurrence.^{3,4} Therefore, novel treatment strategies are of utmost importance to improve this condition.

In recent years, chimeric antigen receptor-modified T cells (CAR-T) therapy have demonstrated remarkable efficacy against several malignancies, especially blood tumors, and represent a new type of cancer treatment.⁵ The FDA has approved two types of CAR-T cell products for the treatment of hematological tumors.⁶ Although CAR-T therapy performs well in hematological tumors, they have not shown similar efficacy in the treatment of other cancers.⁷ Due to the suppressive tumor microenvironment, good infiltration and existence of CAR-T

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cells in solid tumors is a challenge, and on the other hand, the antitumor T cell function is insufficient activated.^{8,9} Studies have shown that, except for T cell receptor engagement (signal 1), and co-stimulation (signal 2), cytokine engagement (signal 3) also played a key role in optimal T cell activation for anti-tumor function, which was probably lost in second-generation CAR-T cells.¹⁰ The cytokines of the γc family, such as IL-2, IL-7, IL-15 and IL-21, all transmit signals through the JAK-STAT pathway, and these cytokines are necessary for the activation and proliferation of T cells and NK cells. Kagoya et al recently developed new-generation CAR-T cells, which encode a truncated cytoplasmic domain from the interleukin (IL)-2 receptor and a STAT3-binding tyrosine-X-X-glutamine (YXXQ) motif at the C-terminus of the CAR structure, together with the first T cell receptor (TCR) and second co-stimulatory signaling domain. This new-generation CAR-T cells have proven to significantly enhance the anti-tumor activity of CAR-T cells.¹¹

Based on the above-mentioned CAR-T cell design, we aimed to design enhanced CAR-T cells to effectively and specifically eliminate esophageal cancer. MUC1, a 200 kDa, complex glycoprotein, has two subtypes: a transmembrane type and a secretory type.¹² MUC1 is always overexpressed in various malignancies, including EC.¹³ In a previous study, carcinoma and pericarcinomatous tissues of 108 ESCC patients were analyzed via immunohistochemical staining, which showed that tissue of 70 ESCC patients showed high expression levels of MUC1. In addition, MUC1 was significantly higher expressed in ESCC tissue compared to para-carcinoma esophageal tissue (65.5%:10.0%, $p < 0.01$).¹⁴ Therefore, we designed a type of CAR-T cells that not only targeted MUC1 but also activated cytokine-cytokine interaction signaling, and verified the efficiency of this enhanced CAR-T cell in vitro. The results showed that enhanced MUC1-CAR-T cells had a significant antitumor ability against EC cells, and that the antitumor effects were much better when compared to traditional MUC1-CAR-T cells. Furthermore, in vivo, enhanced MUC1-CAR-T cells survived longer in mice, which improved the efficiency of treatment and reduced relapses. These findings showed that enhanced MUC1-CAR-T cells have significant anti-tumor activity against EC, can overcome the limitations of traditional CAR-T cells for solid tumors, and provide novel strategies for the treatment of EC.

Methods

Cell Lines and Culture Conditions

After obtaining consent from Xinjiang Uygur Autonomous Region People's Hospital, fresh blood was obtained from healthy volunteers. Healthy volunteers provided written informed consent in compliance with the Declaration of Helsinki. Peripheral blood mononuclear cells (PBMC) were isolated from blood by isopycnic gradient centrifugation using Lymphoprep TM (Solarbio, Beijing, China), and then sorted T cells through magnetic beads of human T cell subtype CD3⁺ (Milenyi Biotec Inc, Auburn, CA, USA). Isolated T cells were resuspended and cultured in X-VIVO-5 medium (Lonza, Basel, Switzerland) supplemented with 5% human AB serum (Valley Biomedical Inc, Winchester, VA, USA), 10 mM N-acetylcysteine (Sigma Aldrich, St. Louis, MO, USA) and 300 U/ml human IL-2 (PeproTech, Rocky Hill, CT, USA).

EC cell lines (Eca-109, TE10, TE13, and OE19 cells) were acquired from the American Type Culture Collection (ATCC, USA). TE13 cells and TE10 cells were cultured in RPMI-1640 medium (Hyclone, Logan, UT, USA); and Eca-109 cells and OE19 cells were cultured in Dulbecco's Modified Eagle Medium (DMEM) medium (Hyclone, L. L., CA, USA). Cell culture medium was supplemented with 10% fetal bovine serum (FBS), 2 mmol/L-glutamine (Gibco, Gaithersburg, MD, USA), 100 U/mL penicillin, and 100 μ g/mL streptomycin (Sangong Biotech, Shanghai, China).

qPCR Assay

Cells were lysed with TRIzol to extract total RNA. The purity and concentration of RNA were detected with a micro-nucleic acid analyzer, and the integrity was checked by agarose gel electrophoresis; cDNA was synthesized by a reverse transcription kit and used as a template for qPCR detection. PCR primer sequence: F is 5'-CTTTTGTACTGTAATCGTTCATGGTTTGAATGATG-3', R is 5'-CATCATTCAAACCATAGAACGATTACAGTACAAAAAG-3'; GAPDH F is 5'-TGGGTGGCAGTGTGGCA-3', R is 5'-GGAGAAGGCTGGGGCTCAT-3'. Reaction conditions: pre-denaturation at 94°C for 1 minute; denaturation at 95°C for 5 seconds; renaturation at 60°C for 30 seconds; and extension at 72°C for 60 seconds; a total of 38 cycles. The melting curve was analyzed, and the relative expression of CD3 ζ was calculated by the 2- $\Delta\Delta$ CT method.

Lentiviral Engineering of T Cells

T cells were stimulated for 48 h with anti-CD3/anti-CD28 antibodies immobilized on tosyl-activated paramagnetic beads (Invitrogen, Carlsbad, CA, USA) prior to infection. After stimulation, 1×10^6 T cells were transduced with lentivirus supplemented with polybrene (Yeasen Biotech, Shanghai, China) at a multiplicity of infection (MOI) of 10. Cells were centrifuged at 32°C, 1200 g for 60 min and incubated overnight at 37°C with 5% CO₂. Replace with fresh medium 24 h after virus infection. The expression of CAR gene was detected by flow cytometry and qPCR at 5 days after lentivirus transfection.

Flow Cytometry

After centrifugation, cells were suspended and washed three times with FACS wash buffer (1 x PBS containing 0.5% BSA and 0.03% sodium azide). Then, cells were stained with an antibody directed against MUC1 (BD, San Jose, CA, USA). To detect phosphorylated STAT3 and STAT5 in T cells, anti-human pSTAT3 (eBioscience, Santiago, CA, USA) and anti-human pSTAT5 (eBioscience, Santiago, CA, USA) monoclonal antibodies were used for staining. After 5 weeks of co-incubation with target cells, the ligands of PD-1, TIM-3 and LAG-3 on CAR-T cells were detected by anti-human CD279 (BD, CA, USA), anti-human CD66 (eBioscience, Santiago, CA, USA) and anti-human CD28 (eBioscience, CA, USA) antibodies, respectively. Moreover, anti-human TNF- α (BD, CA, USA) and anti-human IFN- γ (BD Bioscience, Franklin, NJ, USA) antibodies were used to investigate the level of intercellular TNF- α and IFN- γ in CAR-T cells. In addition, the CD3-PE/CD4-FITC/CD8-PE TruCOUNT kit (BD Bioscience, Franklin, NJ, USA) was used to determine the number of human CAR-T cells in peripheral mouse blood. CD4 + and CD8 + T cells were quantified according to the manufacturer's instructions.

Enzyme-Linked Immunosorbent Assays

A total of 1×10^4 target cells were co-cultured with target cells in a U-shaped 96-well plate at a ratio of 2:1. After 24 hours of incubation, the supernatant was harvested by centrifugation, and used for the detection of IL-2, IFN- γ , and TNF- α levels secreted by CAR-T cells by ELISA assay (MultiSciences, Hangzhou, China). At 9 days after T cell transfusion, 200 μ L of peripheral blood was collected from experimental mice, and serum cytokines, including IFN γ , IL-2, and TNF α were analyzed by ELISA (MultiSciences, Hangzhou, China).

Co-Culture Experiment

To evaluate the cytotoxicity and proliferation of CAR-T cells, TE13 cells were cultured in a 6-well plate at 1×10^6 /well in RPMI-1640 medium without cytokines. After four days, effector cells (CAR-T cells) were added to the plate at an effector-to-target ratio of 1:40 without additional exogenous cytokines. Cells were collected every 3 days thereafter, and tumor cells (CD3 negative) and T cells (CD3 positive) were quantified by flow cytometry.

Xenograft Mouse Models and Living Imaging Assays

Female NOD-SCID IL-2 receptor gamma null (NSG) mice (aged 5–7 weeks) were housed in the Experimental Animal Research Center of Xinjiang Uygur Autonomous Region People's Hospital. All mice were cared for in accordance with the Guide for the Care and Use of Laboratory Animal published by the National Academic Research Council. Written consent was approved by the Animal Care and Committee of Xinjiang Uygur Autonomous Region People's Hospital. NOD-SCID IL-2 receptor gamma null (NSG) mice were purchased from Shanghai Runnuo Biotechnology Co., Ltd. (Shanghai, China) and fed in standard sterile room with daily monitoring. Xenograft models were established by a subcutaneous injection with TE13 cells mixed with Matrigel into different groups of mice. Four days after inoculation, PBS and 1×10^7 MUC1-CAR-T cells, or enhanced MUC1-CAR-T cells were injected in the tail vein. Bioluminescence analysis was performed by a Xenogen IVIS Spectrum System (Life Technologies, New York, NY, USA) every 2–3 days. When mice reached euthanasia criteria, they were euthanized. For the PDX model, tumor-bearing mice with a tumor size range of 100 mm³ were randomly divided into a control group and an experimental group (n = 6). All mice were injected with 1×10^7 CAR-T effector cells via the tail vein. The tumor volume was measured every 3 days. Mice were sacrificed when they lost more than 20% of their initial body weight, when they were unable to move, or when the tumors ulcerated in the control group.

Quantitation of T Cell Counts

In a previous animal experiment, 100 μ L of blood were collected from mice on day 9 after tumor cell inoculation to measure T cell proliferation in vivo. The collected blood samples were quantified for T cell counts. In addition, the number of CD8 + and CD4 + T cells were determined.

Immunohistochemistry Assay

To evaluate the infiltration of human T cells in the xenograft model after treatment, formalin-fixed paraffin-embedded tumor tissue sections were assessed by IHC. Heat-induced epitope retrieval was carried out using a decloaking chamber at 95°C for 20 min in a citrate-based low pH buffer. After inactivation of peroxidases and blocking using H₂O₂ and 2.5% horse serum, rabbit anti-CD8 antibody (1:150, Thermo Scientific) was incubated overnight. HRP anti-rabbit IgG (1:200, Thermo Scientific) was then applied to the sections and revealed with DAB peroxidase substrate solution. Finally, imaging was performed using OLYMPUS BX53 microscope.

Statistical Analysis

GraphPad Prism 6.0 was used for statistical analysis. The Student's *t*-test was used to evaluate significant data, and *P* < 0.05 was considered statistically significant.

Results

Construction and Selection of MUC1-CAR-T Cells

In this study, we built a MUC1 targeted second-generation CAR sequence (BB-z), with CD3 ζ mediated T cell activation and a 4-1BB co-stimulatory signal. In addition, and based on previous studies, a cytokine receptor interaction domain was added in the former sequence and named enhanced CAR sequence (δ IL2RBB-z) (Figure 1A). After lentivirus transfection, the positive rate of the CAR was used to identify the transfection efficiency of CAR-T cells by flow cytometry (Figure 1B and C). Moreover, the quantity of the exogenous CD3 ζ gene in transfected T cells was evaluated using qPCR to confirm that CAR-T cells were successfully constructed (Figure 1D). In the selection part, we performed Western blot (WB) analysis on stored EC cells including Eca-109, TE10, TE13, and OE19 cells. We found that TE13 and OE19 cells overexpressed MUC1, whereas TE10 cells showed a lower expression, and Eca-109 cells rarely expressed MUC1 (Figure 1E and F). Subsequently, we performed flow cytometry (Figure 1G and H) to verify the experimental results of WB analysis. In the following experiment, we selected MUC1-negative EC cell Eca-109 cells as the negative control group, and TE13, TE10, and OE19 cells as experimental groups.

The Investigation of Antitumor Function for Enhanced MUC1-CAR-T Cells in vitro

We first verified whether the constructed enhanced CAR-T cells could effectively induce the JAK-STAT signaling pathway. For this experiment, TE13 cells were used as target cells and incubated with three types of effector T cells for 2 hours at a target-to-effector ratio of 2:1. The effector T cells were transfected with an empty vector (Mock group), a second-generation group (BB-z group), and an enhanced CAR-T cell group (δ IL2RBB-z group), respectively. Following 2 hours of incubation, the levels of pSTAT3 and pSTAT5 in effector cells were determined by flow cytometry because the phosphorylation level of STAT3 and STAT5 represents the activation state of interleukin (IL)-2 receptor and a STAT binding tyrosine-X-X-glutamine (YXXQ) motif in enhanced CAR-T cells. The data showed that pSTAT3 and pSTAT5 levels in the δ IL2RBB-z group were significantly higher when compared to those in the BB-z group (Figure 2A and B).

Next, we co-incubated the 4 types of tumor cells with effector cells for 24 hours and evaluated secreted levels of IL-2, IFN- γ , and TNF- α . The levels of all cytokines secreted by MUC1-CAR-T cells were higher when compared to the control. Only basal levels of IL-2, IFN- γ , and TNF- α were detected in Eca-109 and MUC1-CAR-T cells. In addition, no significant differences were observed between BB-z and δ IL2RBB-z groups at this point in time (Figure 2C–E). Finally, we explored the cytotoxicity ability of MUC1-CAR-T to target cells. We co-incubated the 4 tumor cell lines with effector cells at 3:1, 1:1, and 1:3 ratio, respectively. After 24 hours of incubation, the level of Lactate dehydrogenase (LDH) released in medium was used to evaluate the cytotoxicity. The results revealed that by increasing the target–effector ratio, MUC1-CAR-T cells presented a strong dose-dependent cytotoxic effect on TE13, TE10, and OE19 cells, which overexpressed MUC1. This effect, however, was not observed in MUC1-negative Eca-109 cells. Moreover, the cytotoxicity of the δ IL2RBB-z group was further increased when compared with the BB-z group (Figure 2F–I). The cytotoxicity results were confirmed by microscopy (Figure 2J).

Investigation of the Activation for Enhanced MUC1-CAR-T Cells After Long-Term Stimulation in vitro

To evaluate the anti-tumor effect of MUC1-CAR-T cells after long-term stimulation in vitro, TE13 was incubated

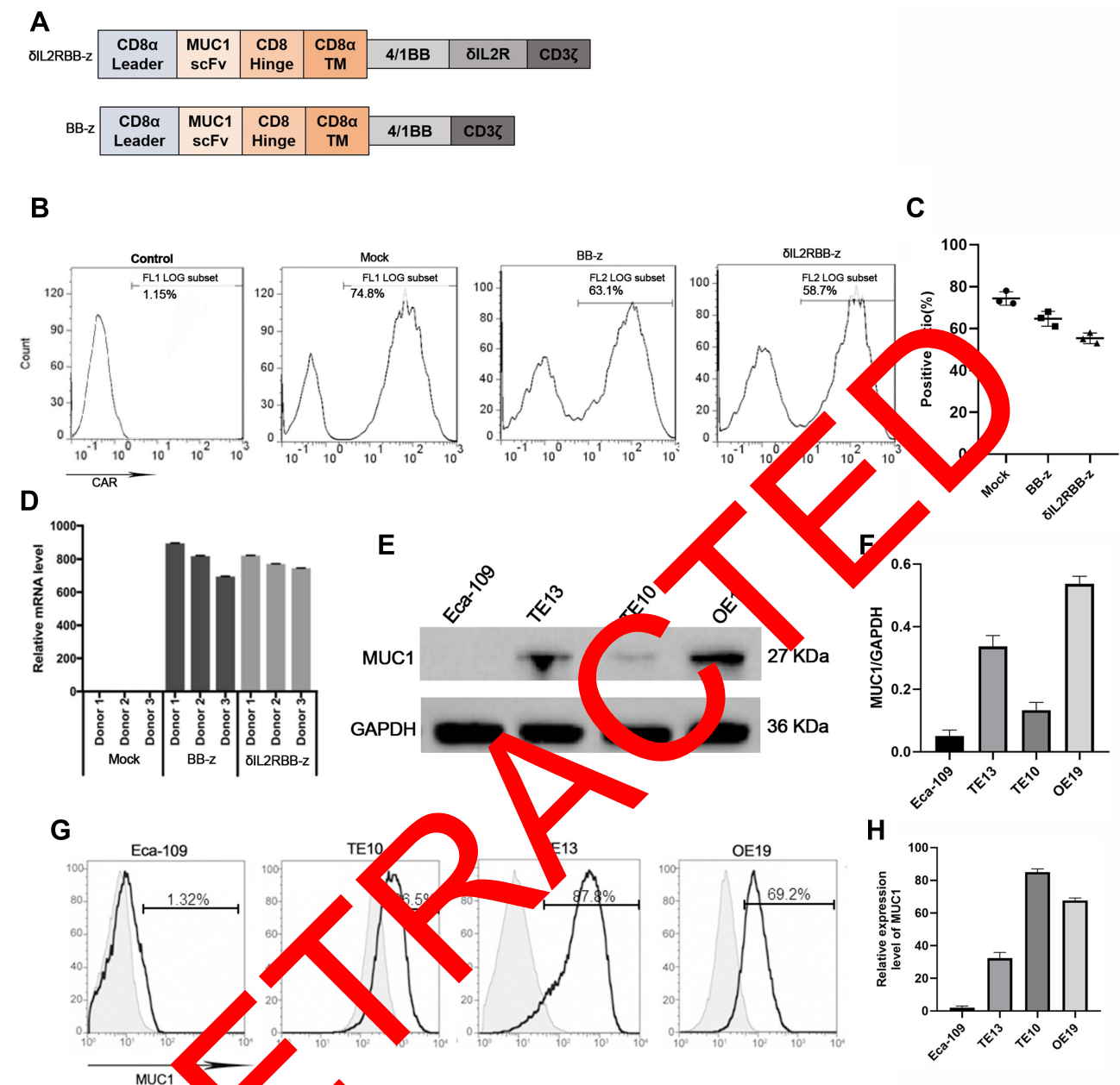


Figure 1 Construction of effector cells and selection of target cells. **(A)** The structure of the CAR gene of effector cells. **(B and C)** On day 5 after T cell transfection with the lentivirus encoding CAR gene, the positive rate of MUC1-CAR-T cells by flow cytometry. **(D)** The expression of the exogenous CD3 ζ gene in transfected T cells by qPCR. **(E and F)** The expression of MUC1 antigen in esophageal cancer cells by Western blot analysis. MUC1 is around 27kD and GAPDH is used as parameter. **(G and H)** The expression of MUC1 in Eca-109, TE10, TE13, and OE19 cells by flow cytometry.

with each group of effector cells for 12 days, and the number of tumor cells and CAR-T cells were counted. The results showed that in the BB-z group, there was no significant proliferation of CAR-T cells, and tumor cells could not be effectively eliminated. On the contrary, in the δ IL2RBB-z group, enhanced MUC1-CAR-T cells showed strong ability in self-proliferation and elimination of tumor cells during the long-term co-incubation, thereby indicating enhanced MUC1-CAR-T cells played a more

effective role in anti-tumor when compared to traditional CAR-T cells (Figure 3A). To study the proliferation capacity of enhanced MUC1-CAR-T cells, we prolonged the co-incubation time in vitro and showed that when compared with CAR-T cells, which gradually lost proliferation in the BB-z group, cells in the δ IL2RBB-z group continued to increase over time after 5-weeks of co-incubation (Figure 3B). The function of CAR-T cells was also investigated by flow cytometry, measuring the expression levels

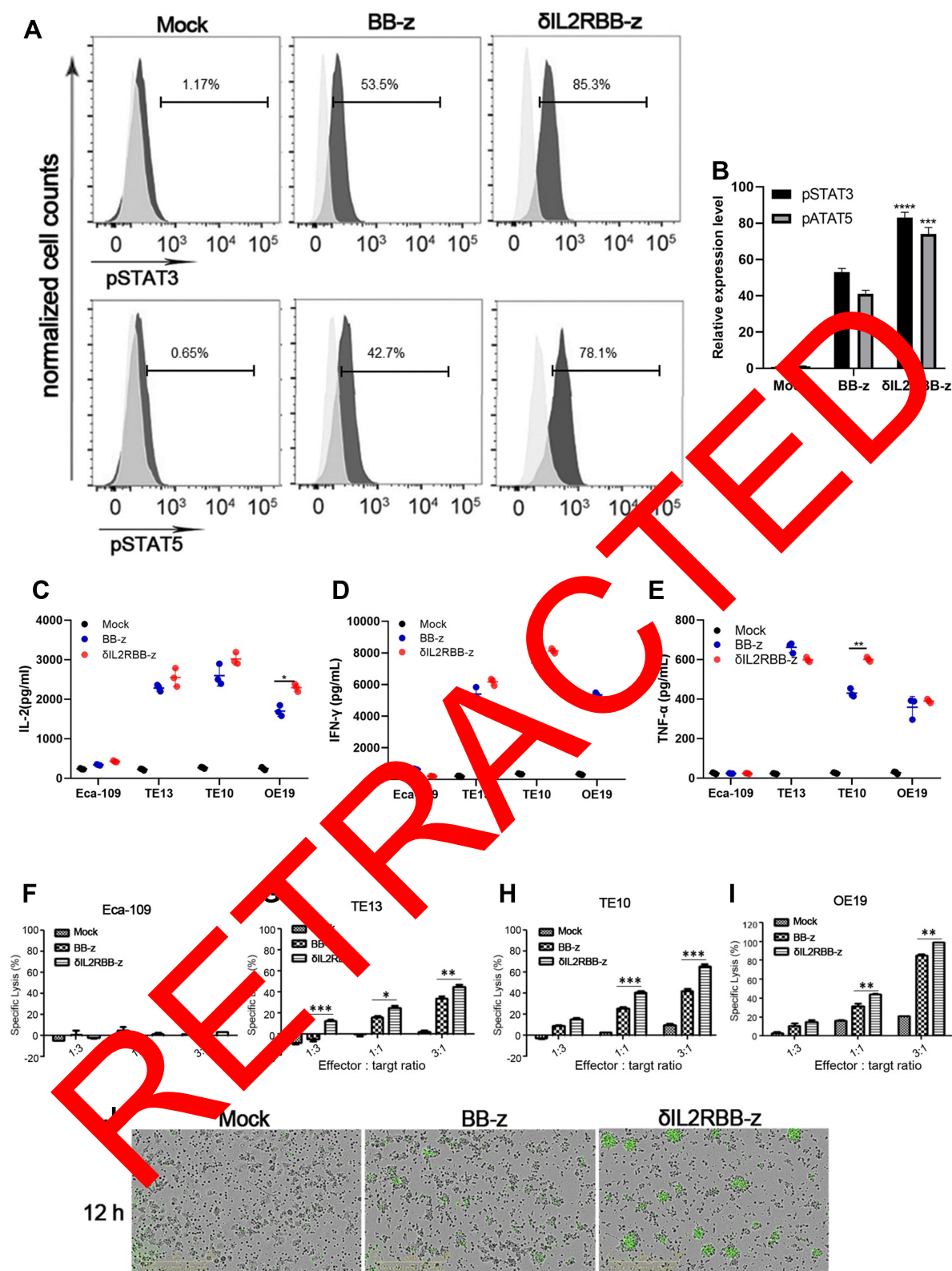


Figure 2 Investigation of the anti-tumor function for enhanced MUC1-CAR-T cells in vitro. (**A** and **B**) Changes in pSTAT3 and pSTAT5 by flow cytometry. Effector cells and target cells were incubated for 4 hours at an effector-target ratio of 2:1, then cells were collected for flow cytometry. (**C–E**) 1×10^4 target cells were taken and incubated with the target cells for 24 h at a ratio of 2:1, then the levels of IFN- γ , IL-2, TNF- α were measured. (**F–I**) A total of 1×10^4 target cells were taken, and incubated with effector cells for a total of 24 h at an effector-target ratio of 3:1, 1:1, 1:3, respectively. Then, the LDH content in the supernatant was measured. (N = 3, the bar value represents the degree of dispersion, Two-way ANOVA, *P < 0.05, **P < 0.01, ***P < 0.001, ****P < 0.0001). (**J**) Real-time microscopic images of co-incubation of target cells labeled YOYO-1 (green, dead cell labeling reagent).

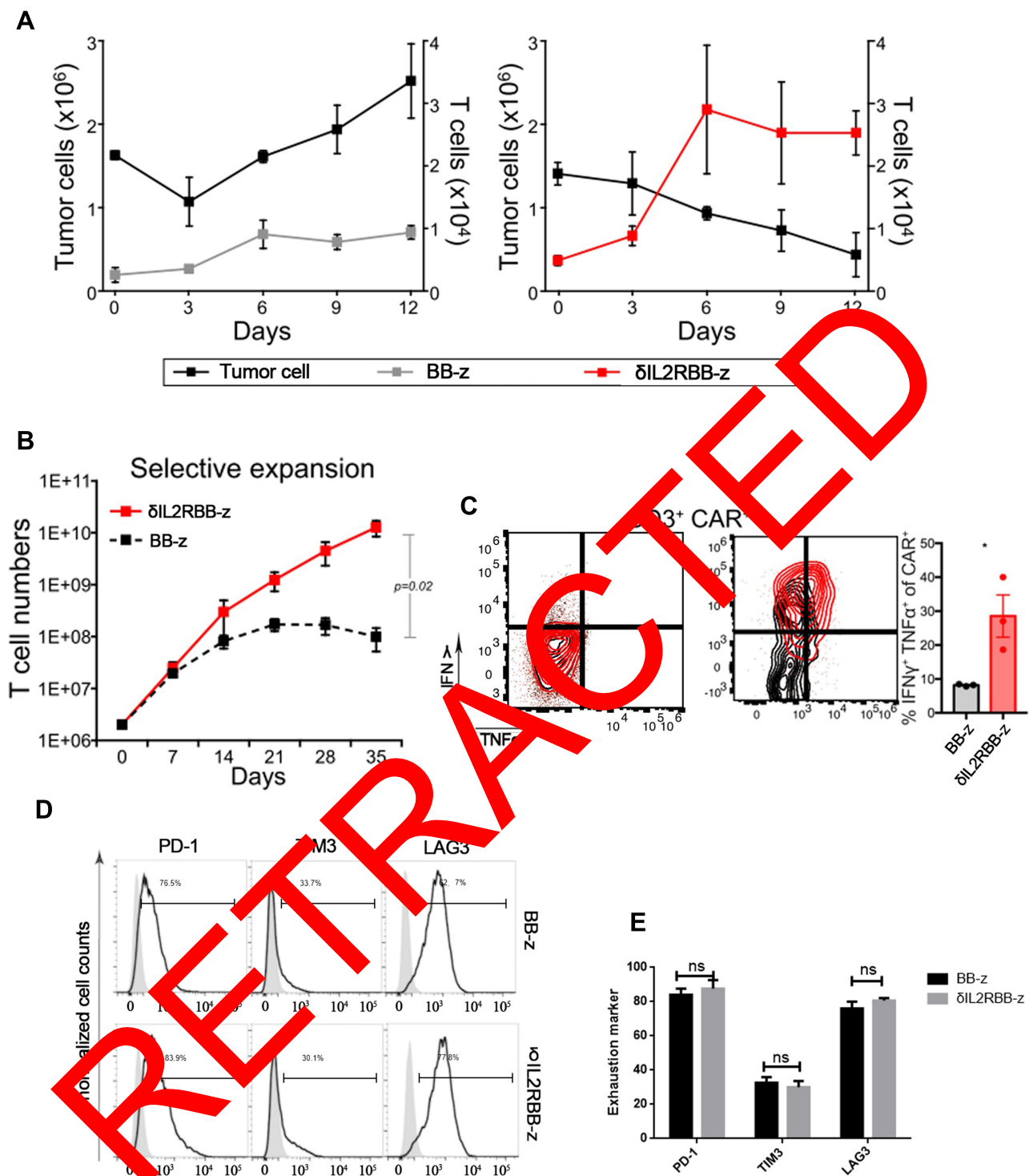


Figure 3 Validation of enhanced MUC1-CAR-T cells after long-term stimulation in vitro. **(A)** The proliferation and accumulation of traditional and enhanced MUC1-CAR-T cells, and the number of tumor cells during continuous co-culture. **(B)** The number of CAR-T cells during the 5-week incubation, counted every 7 days. **(C)** After 5 weeks of incubation, T cells were collected and the level of TNF- α and IFN- γ , secreted by CAR-T cells, was determined by flow cytometry. **(D)** After 5 weeks of incubation, T cells were collected and flow cytometry was applied to determine the expression of cell depletion biomarkers on the surface of T cells, including PD-1, TIM-3, and LAG-3. **(E)** The expression of PD-1, TIM-3, and LAG-3 ($n = 3$, bar value represents the degree of dispersion, Two-way ANOVA, ns is no significant difference, * $P < 0.05$).

of IFN- γ and TNF- α , which revealed that enhanced MUC1-CAR-T cells had stronger effector functions when compared to traditional CAR-T cells (Figure 3C).

Furthermore, in previous studies, it was shown that excessive activation of CAR-T cells was accompanied by upregulated secretion of suppressive cytokines, which might

influence the function of CAR-T cells. In this study, we continuously prolonged the co-incubation time into 35 days, and found no significant differences in the expression of PD-1, TIM3, and LAG3 on the surface of T cells in the δ IL2RBB-z group and the BB-z group (Figure 3 D, E). Thus, enhanced MUC1-CAR-T cells could maintain the ability of proliferation and anti-tumor under long-term stimulation of tumor cells, and are expected to have better therapeutic effects in the future.

Antitumor Ability of Enhanced MUC1-CAR-T Cell in a Heterologous Tumor Model in vivo

Using NOD/SCID mice, which bear TE13 subcutaneous xenograft tumors, we further compared the in vivo cytotoxicity between traditional and enhanced MUC1-CAR-T cells. We monitored the survival of CAR-T cells in mice through collecting the fluorescence intensity of T cells through in vivo imaging. The imaging results (Figure 4A) showed that both types of MUC1-CAR-T cells could proliferate in the mouse model, however, when compared with the fluorescence intensity level, in the δ IL2RBB-z group, CAR-T cells proliferated more vigorously and lasted longer when compared to the BB-z group (Figure 4B). In addition, when evaluating the tumor volume, both the δ IL2RBB-z and BB-z groups showed reduced tumor growth, but enhanced MUC1-CAR-T cells showed more effective antitumor function when compared to traditional MUC1-CAR-T cells (Figure 4C). The degree of infiltration of CAR-T cells into tumor tissues in vivo was highly correlated with the efficacy of CAR-T cells. Therefore, we performed the hematoxylin and eosin (HE) staining and immunohistochemical staining of mouse tumor and found that the number of infiltrating CD8⁺ T cells in tumor tissue of the enhanced MUC1-CAR-T group was higher when compared to that of the conventional MUC1-CAR-T group (Figure 4D, E). In summary, the results of our in vivo experiments are consistent with the in vitro studies, thereby showing that although enhanced MUC1-CAR-T cells and traditional MUC1-CAR-T cells have obvious antitumor effects on esophageal cancer, enhanced MUC1-CAR-T cell has a better function.

Enhanced MUC1-CAR-T Cells Significantly Improve the Antitumor Function in the PDX Model

To further investigate the function of MUC1-CAR-T cell, we established a PDX mouse model of human EC.

Immunohistochemical results of the patient's cancer tissue showed high expression of the MUC1 antigen (Figure 5A). Fifteen days after tumor implantation, mice were intravenously injected with PBS, MUC1-CAR-T, or enhanced MUC1-CAR-T cells. The tumor volume was measured every 3 days thereafter (Figure 5B). After T cell injection, the level of cytokines and the T cell survival rate in mouse peripheral blood was evaluated for 9 days. Our data showed that more MUC1-CAR-T cells were observed in the δ IL2RBB-z group when compared to the BB-z group, and that levels of IL-2, IFN- γ , and TNF- α in the δ IL2RBB-z group were much higher when compared to those in the BB-z group (Figure 5C and E). The survival curves of mice in each group showed that the survival time of mice in the IL2RBB-z group was significantly longer when compared to that in the BB-z group (Figure 5D). Finally, immunohistochemical results showed that T cells infiltrated to a higher degree in the δ IL2RBB-z group, which was consistent with the better treatment effects observed (Figure 5F and G). Taken together, data obtained in the PDX model confirmed that enhanced MUC1-CAR-T cells have a better antitumor effect when compared to traditional MUC1-CAR-T cells.

Discussion

Because of the excellent clinical effects of CAR-T cell therapy in hematological malignancies, there is increased attention for CAR-T cells for solid cancer in the field of immunotherapy.¹⁵ Several tumor antigens, including EGFR, Her2, and VEGF are overexpressed in EC; therefore, CAR-T cell therapy has broad application prospects in this malignant tumor type.^{16–18} However, due to the suppressive effects of the tumor microenvironment on CAR-T cells, and incompletely activated second-generation CAR-T cells, CAR-T cells often show poor activity in solid tumors.¹⁹ To improve the activation of CAR-T cells, based on a previous study, we adopted a previously reported CAR pattern in which the CAR sequence contains the intracellular segment of the IL2R β chain, and a YXXQ motif, which binds to STAT3 to provide CAR-T cells with cytokine signals, enhance CAR-T cell proliferation, and anti-tumor activity.¹¹ Therefore, these enhanced CAR-T cells are expected to be an effective strategy in the treatment of solid tumors.

Optimal T cell activation and proliferation require multiple signals, including activation of T cell receptors (signal 1), costimulatory signals (signal 2), and activation of cytokine receptors (signal 3).²⁰ However, the current

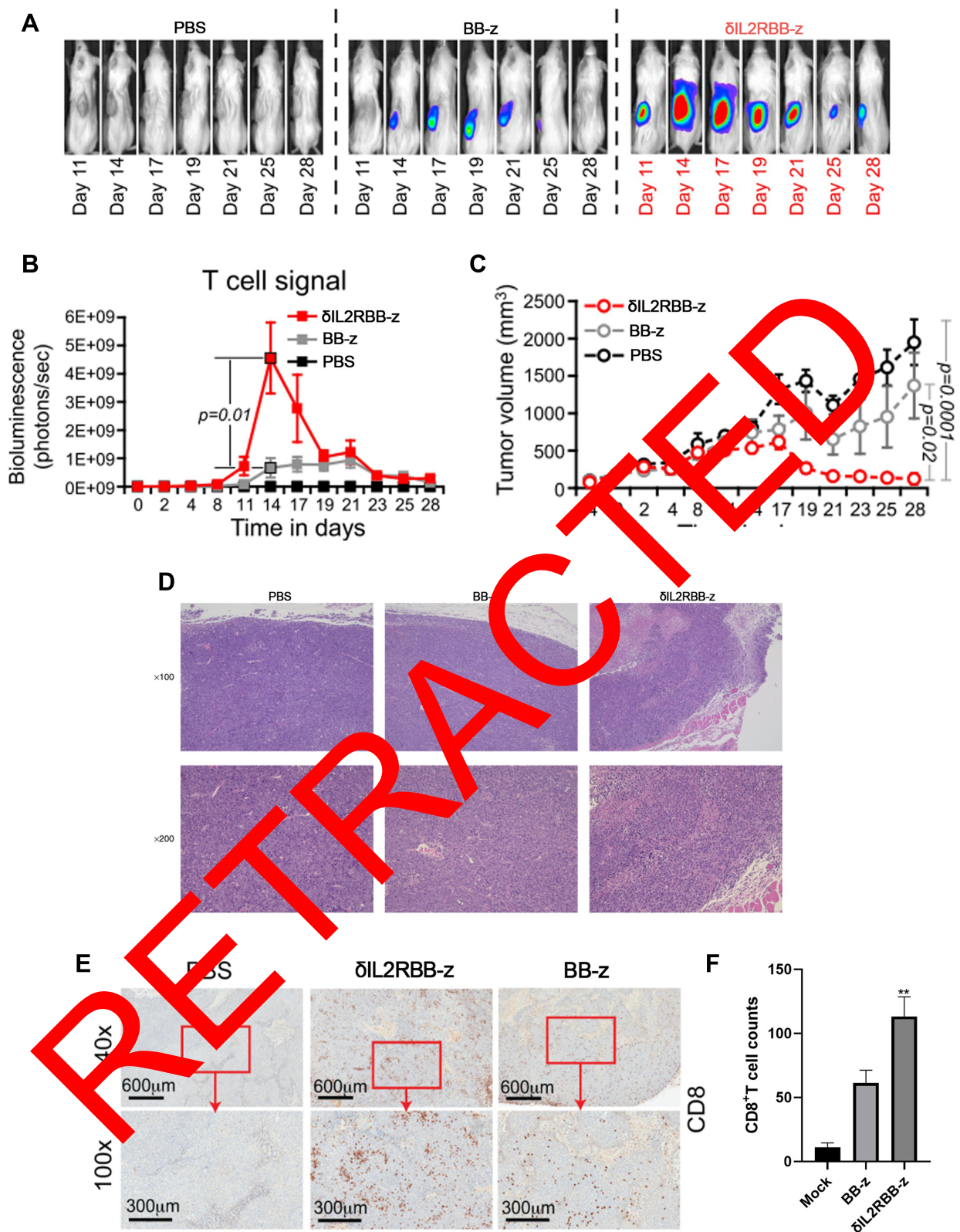


Figure 4 Anti-tumor ability of enhanced MUC1-CAR-T cells in a heterologous mouse tumor model. **(A)** Real-time imaging of MUC1-CAR-T cells in vivo in the TE13 xenograft model. **(B)** The changes in MUC1-CAR-T cell fluorescence intensity after co-inoculation with tumor cells ($n = 5$, the bar value represents the dispersion, Two-way ANOVA). **(C)** Change in tumor volume in the xenograft mouse model ($n = 5$, bar value represents the dispersion, Two-way ANOVA). **(D)** The results of HE staining. **(E and F)** The results of immunohistochemistry of CD8⁺ T cell infiltration in tumor tissues ($n = 3$, bar value represents the degree of dispersion, One-way ANOVA, $**P < 0.01$). Data represent three independent experiments.

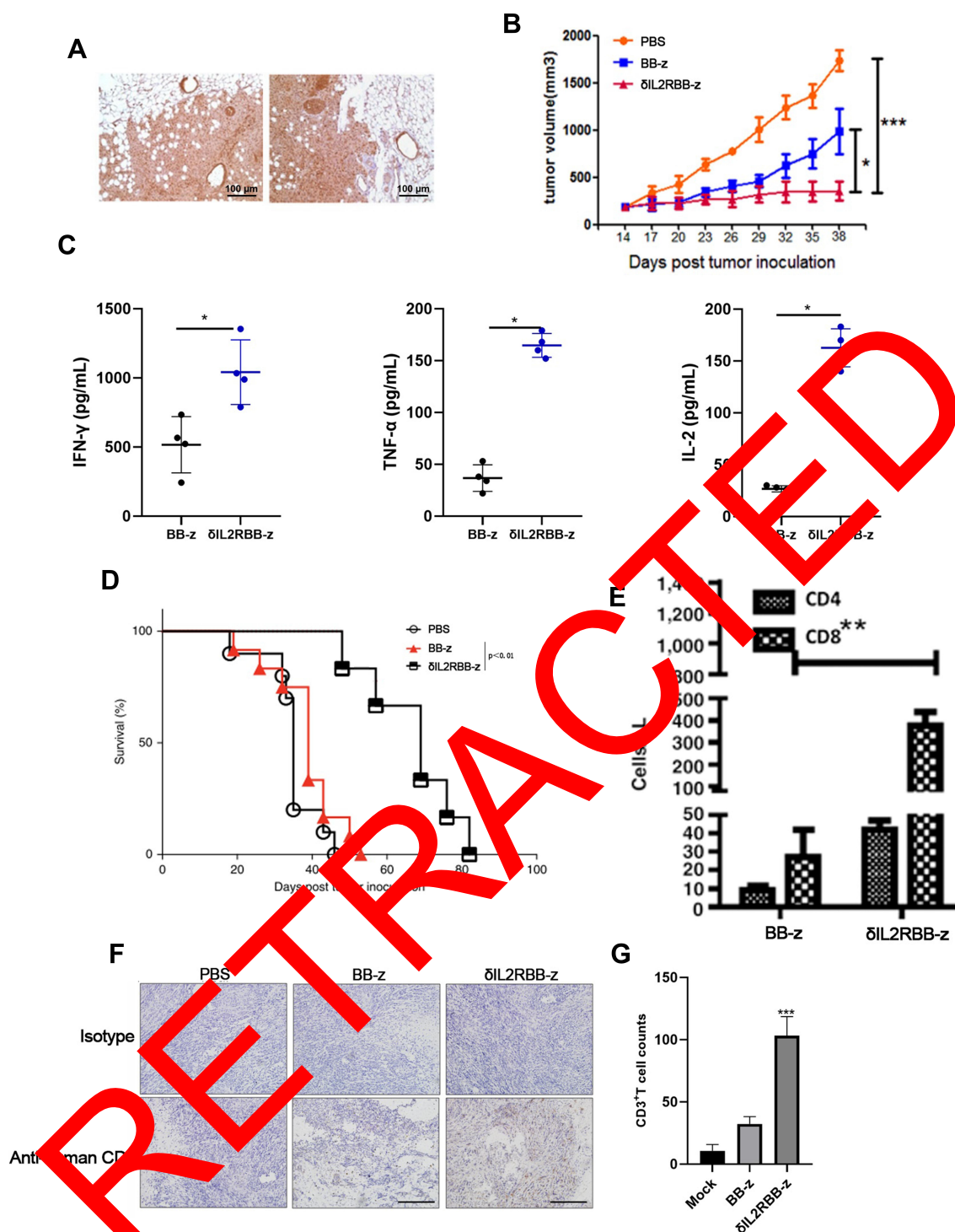


Figure 5 Enhanced MUC1-CAR-T cells significantly improved antitumor function in the PDX model. **(A)** MUC1 antigen expressed in patient-derived cancer tissue (detected by immunohistochemistry). **(B)** After the PDX model was established, CAR-T cells were reinfused in experimental group through tail vein injection, and PBS was reinfused in the control group. Tumor volume was measured every 3 days with a Vernier caliper (n = 6, the bar value represents the degree of dispersion, Two-way ANOVA, *P < 0.05, ***P < 0.001). **(C)** On the 9th day, 200 μ L of mouse peripheral blood was taken, and levels of IFN- γ , TNF- α , and IL-2 were determined (n = 6, bar value represents the degree of dispersion, t-test, *P < 0.05). **(D)** Survival curves of PDX model mice under different treatments (P < 0.01 by Log rank Mantel-Cox test with a 95% CI of 0.4–3.1). **(E)** On the ninth day, 200 μ L of mouse peripheral blood was taken and the number of CD4⁺ and CD8⁺ T cells were counted (n = 6, the bar value represents the degree of dispersion, Two-way ANOVA, **P < 0.01). **(F and G)** Immunohistochemical staining of CD8⁺ T cell infiltration in tumor tissues (n = 6, the bar value represents the degree of dispersion, One-way ANOVA, ***P < 0.001). Data represent three independent experiments.

mainstream second-generation CAR structure only contains the CD3 ζ (TCR signal) domain and the costimulatory domain, but not the signal 3 domain. Some clinical and pre-clinical studies have explored the combination of CAR-T cells and cytokines to achieve the goal of enhancing the anti-tumor activity of CAR-T cells. Oladapo O. Yeku et al used CAR-T cells to autocrine IL-12 to make CAR-T cells have stronger proliferation capacity and persistence in the body.²¹ Adachi et al designed CAR-T cells that secrete IL-7 and CCL19 at the same time and proved that they not only make CAR-T cells more proliferative but also increase the tumor infiltration ability of CAR-T cells.²² However, these methods also have certain limitations. For example, the function of these CAR-T cells to secrete cytokines is not regulated, so it is likely to cause a cytokine storm. In this study, the direct integration of the IL-2 receptor domain into the CAR structure can not only enhance the proliferation and anti-tumor activity of CAR-T cells in an antigen-dependent way but also avoid the possibility of cytokine storms.

In our study, we selected EC cells that overexpressed MUC1 and constructed traditional second-generation MUC1-CAR-T cells as well as enhanced MUC1-CAR-T cells to verify whether this type of enhanced MUC1-CAR-T cells showed better antitumor activity against esophageal cancer. Our data showed that both types of MUC1-CAR-T cells eliminated MUC1-positive EC cells in vitro; however, enhanced MUC1-CAR-T cells had a higher ability of proliferation and secretion when compared to traditional MUC1-CAR-T cells. This may be because the JAK-STAT signal provided by the IL-2 receptor recruited more STAT5, which resulted in a stronger proliferation level of CAR-T cells.²³ At the same time, the YXXQ sequence can recruit more STAT3 and The CAR-T cells produce more memory phenotypes.²⁴ In addition, the longer the co-incubation with tumor cells, the more cytotoxic the enhanced MUC1-CAR-T cells.

Furthermore, the constructive enhanced MUC1-CAR-T cells achieved significant antitumor activity in EC, providing us with a reference treatment strategy. We could choose potential targets in EC, including EGFR and Her2, and broaden the application of enhanced MUC1-CAR-T cell in the treatment of EC.^{25,26}

Conclusion

In this study, we have proven that this type of enhanced MUC1-CAR-T cells exhibited good antitumor activity

through various in vivo and in vitro experiments. Our work has some limitations: CAR-T cells that target a single MUC1 antigen still have a risk of being off-target.²⁷ Therefore, we considered adopting a dual-receptor CAR-T cell strategy in the future to reduce its off-target effects.^{28,29} The improved anti-tumor activity of enhanced MUC1-CAR-T cells provides a novel treatment strategy for the treatment of EC in the future.

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Disclosure

The authors declare that they have no conflicts of interest.

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