

Optimizing Blood Stem Cell Transplants Through Cellular Engineering

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Abstract

Haematopoietic stem cell transplants (HSCT) are used in the treatment of blood cancers, autoimmune diseases, and metabolic disorders. Over 1.5 million transplants have been performed around the world thus far. In an attempt to enhance the efficacy of the cells used for transplantation, efforts are underway to use cellular engineering to increase cell numbers through: (1) the expansion of hematopoietic stem and progenitor cells (HSPC); (2) cellular subset selection to remove cells that cause graft-versus-host disease (GvHD), while adding back cells, which can mediate anti-tumor and anti-viral immunity; (3) the use of immune regulatory cells, such as mesenchymal stromal cells (MSC) and regulatory T cells (Tregs) to control GvHD; (4) the use of immune effector cells to mount immunological control of tumor cells before, after, or independent of blood stem cell transplants.

Key words hematopoietic stem cell transplants, haematopoietic stem and progenitor cell expansion, cell selection in haploidentical transplantation, immune regulatory cells, immune effector cell therapy

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Introduction

Haematopoietic stem cell transplants (HSCT) are used in the treatment of blood cancers, autoimmune diseases, and metabolic disorders¹⁻³, with over 1.5 million transplants performed thus far around the world and over 50,000 performed annually⁴. Cells used for HSCT are obtained from bone marrow (BM), peripheral blood (PB), or umbilical cord blood (UCB). There are two types of HSCTs: (1) autologous HSCTs, wherein hematopoietic stem and progenitor cells (HSPC) are taken from the patients themselves; (2) allogeneic HSCTs, wherein the cells are taken from a donor⁵. However, allogeneic HSCT performed using blood cells from a donor could lead to graft-versus-host disease (GvHD), a potentially fatal condition in which donor immune cells attack the recipient's body⁵. The lack of suitable human leukocyte antigen (HLA)-matched donors has been overcome by using haploidentical and UCB donors. Haploidentical ("half-matched") family

donor transplants have been successful through the use of *in vitro* and *in vivo* T cell depletion methods, which reduce donor T cells and GvHD. UCB transplants have significant benefits due to their ability to perform HLA-mismatched transplants without *in vivo* or *in vitro* T cell depletion. Furthermore, UCB grafts retain a strong graft versus tumor (GVT) effect while having a lower incidence of GvHD compared to the other two sources of HSPCs⁷. However, UCB contains limited numbers of HSPCs, which has led to delayed engraftment and immune reconstitution, as well as increased rate of graft failure^{6,8}. Currently, the main challenge associated with HSCTs lies in the delivery of an adequate number of cells to enable rapid hematological reconstitution while minimizing GvHD and maximizing GVT of infused donor cells. In this review, we discuss methods to improve the outcome of patients, including cell selection in haploidentical transplantations, the use of immune regulatory cells including mesenchymal stromal cells (MSCs) and regulatory T (Treg) cells, HSPC expansion, and im-

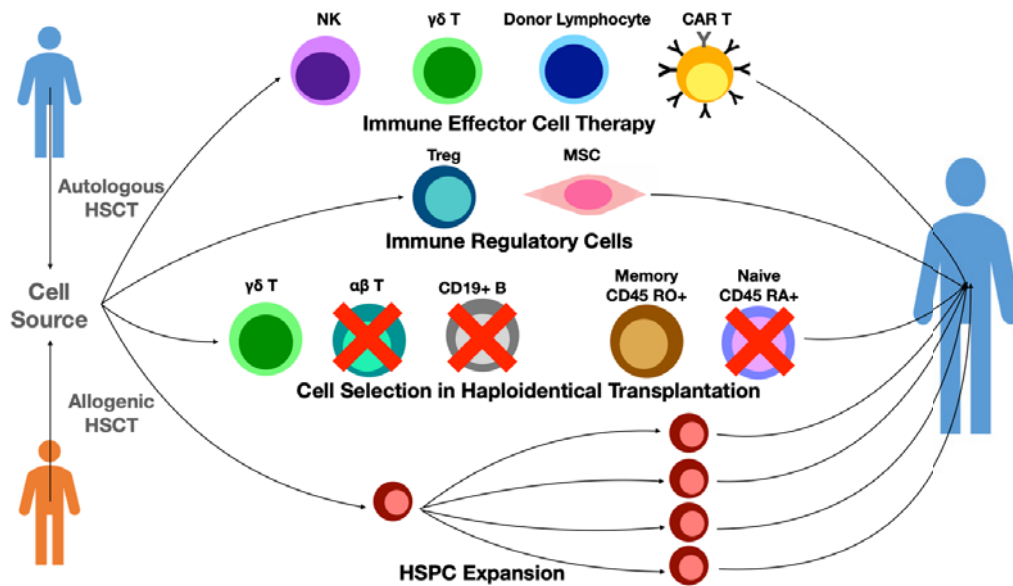


Figure 1. Graphical Abstract

UCB, Umbilical cord blood; CB, cord blood; UCBT, umbilical cord blood transplantation; GvHD, Graft-versus-host disease; SR-1, StemReginin-1

immune effector cell therapy using donor lymphocyte infusions (DLI), chimeric antigen receptor (CAR) T cells, natural killer (NK) cells, and gamma delta ($\gamma\delta$) T cells (**Figure 1**).

HSPC Expansion

Umbilical cord blood expansion (Table 1)

To optimize the outcomes of patients undergoing HSCTs performed using UCB, HSPCs must undergo expansion in order to increase the number of HSPCs, thereby decreasing graft failure rates and increasing survival rates. Several studies have investigated the use of different cultures for UCB expansion. Clinical trials involving transplantation have used NiCord, an *ex vivo* expanded cell product derived from UCB, which uses nicotinamide as the active agent to inhibit differentiation and enhance the functionality of cultured HSPCs^{9, 10}. These trials have shown the multi-fold expansion of CD34+ cells, earlier median neutrophil recovery, and long-term engraftment, with no adverse outcomes associated with the use of NiCord^{9, 10}. In a recent study, 36 patients underwent transplantation with NiCord as a stand-alone graft between 2013 and 2017. After NiCord expansion, a 33-fold increase in the CD 34 content of the graft was observed, and by 21 days after transplantation, 89% of NiCord recipients had achieved neutrophil engraftment. Furthermore, neutrophil engraftment was faster for the recipients of NiCord. NiCord recipients also had a higher incidence of platelet engraftment (81%) 100 days after HSCT, with faster platelet engraftment and recovery¹⁰. In another

study conducted with omidubicel, formerly known as NiCord, 125 patients with hematologic malignancies received either omidubicel or standard umbilical cord blood transplantation (UCBT)¹¹. The results showed that the omidubicel transplant recipients had a shorter median time to neutrophil engraftment of 12 days compared to 22 days for patients in the control group. Omidubicel recipients also had a higher cumulative incidence (CI) of neutrophil engraftment, as well as a faster platelet recovery, a lower incidence of bacterial and fungal infections, and they spent more time out of hospital during the first 100 days post-transplant as compared to the control group¹¹.

In addition to NiCord, StemReginin-1 (SR-1) is an aryl hydrocarbon receptor antagonist that has also been studied for its effect on UCB expansion and HSCT¹². In a phase I/II trial, 17 patients received HSC835, which was the product of the expansion of UCB CD34+ cells using SR-1¹². After 15 days in SR-1 expansion culture, the median number of total CD34+ cells was found to increase 330-fold from an initial 4.4×10^6 cells to a final $1,440 \times 10^6$ cells. Patients who had received HSC 835 all demonstrated neutrophil recovery, which was achieved faster than the control group¹². Another expansion technique involves the use of UM171, an HSPC agonist, which has been shown in several studies to successfully expand UCB units^{13, 14}. In one of the studies, 20 patients received a single UM171-expanded UCB transplant, while 12 patients received transplants with single or double unmanipulated UCB. The results showed a 17-fold larger CD34+ cell dose and a 2-fold lower CD3+ T cell dose in UM171 patients, as well as

Table 1. Summary of several clinical trials using expanded UCB for HSCT

Study	Patient group	No. of patients	Outcome
S. Anand <i>et al.</i> [9]	Recipients of UCB expanded <i>ex vivo</i> with nicotinamide (NiCord)	18	12.5 days (median) to neutrophil engraftment. 22% of patients with at least one grade 2-3 bacterial infection. 72.4 days (mean) out of hospital in the first 100 days.
	Control group (recipients of unmanipulated standard single or double UCB grafts)	86	26 days (median) to neutrophil engraftment. 57% of patients with at least one grade 2-3 bacterial infection. 48.6 days (mean) out of hospital in the first 100 days.
M. E. Horwitz <i>et al.</i> [10]	Recipients of single CB unit expanded <i>ex vivo</i> with nicotinamide	36	11.5 days (median) to neutrophil recovery. 34 days (median) to platelet recovery. Cumulative incidence (CI) of grade II to IV acute GvHD (aGvHD) at day 100 of 44%. CI of chronic GvHD (cGvHD) at 2 years of 40%. 51% 2-year probability of overall survival (OS).
	Control group (Recipients of standard UCBT)	146	21 days (median) to neutrophil recovery. 46 days (median) to platelet recovery. CI of grade II to IV aGvHD at day 100 of 56%. CI of cGvHD at 2 years of 30%. 48% 2-year probability of OS.
M. E. Horwitz <i>et al.</i> [11]	Recipients of omidubicel	125	12 days (median) to neutrophil engraftment, CI of neutrophil engraftment of 96%. 37% incidence of infections, 61 days (median) out of hospital in first 100 days post-transplant
	Recipients of standard UCBT		22 days (median) to neutrophil engraftment, CI of neutrophil engraftment of 89%. 57% incidence of infections, 48 days (median) out of hospital in first 100 days post-transplant
J. E. Wagner <i>et al.</i> [12]	Recipients of SR-1 expanded UCBT	17	All patients achieved neutrophil recovery at a median of 15 days. 49 days (median) to platelet recovery. 30 days (median) of hospitalisation.
	Control group (recipients of unmanipulated UCB units)	111	86% of patients achieved neutrophil recovery at a median of 24 days. 89 days (median) to platelet recovery. 46 days (median) of hospitalisation.
M. Dumont-Lagacé <i>et al.</i> [13]	Recipients of a single UM171-expanded CB transplant	20	5.9 months (median) to immunosuppression withdrawal. Lower frequency of severe infections at 1 year post-transplant. More pronounced increase of naive T cell and recent thymic emigrant cells from 3 months to 6 and 12 months post-HSCT. Higher numbers of clonotypes at 6 and 12 months.
	Control group (recipients of single or double unmanipulated CBs)	12	7.1 months (median) to immunosuppression withdrawal.
S. Cohen <i>et al.</i> [14]	Recipients of a single UM171-expanded CB transplant	22	9.5 days (median) to engraftment of 100 neutrophils per μL , 18 days (median) to engraftment of 500 neutrophils per μL . No graft failure occurred.
R. S. Mehta <i>et al.</i> [16]	Recipients of 1 CB unit expanded <i>ex vivo</i> with MSCs and 1 unmanipulated CB after reduced intensity conditioning	27	3 patients with primary graft failure. 12 days (median) to neutrophil recovery. 78% CI of neutrophil engraftment. 28% incidence of grade II-IV aGvHD. 29% of incidence of cGvHD. 28% disease-free survival (DFS) and 32% OS at 2 years.
	Control group (recipients of 2 unmanipulated CB units)	51	4 patients with primary graft failure. 16 days (median) to neutrophil recovery. 67% CI of neutrophil engraftment. 27% incidence of grade II-IV aGvHD. 20% of incidence of cGvHD. 25% DFS and 34% OS at 2 years.

UCB, Umbilical cord blood; CB, cord blood; UCBT, umbilical cord blood transplantation; GvHD, Graft-versus-host disease; SR-1, StemRegenin-1

a shorter median time to immunosuppression withdrawal for the UM171 cohort, compared to the control cohort¹³. A novel azole small molecule, C7, was used in the *ex vivo* expansion of UCB HSPC, and the results showed that the addition of C7 could boost the expansion of hematopoietic progenitor cells (HPCs) by large amounts. The culturing of UCB CD34+ cells in the presence of C7 resulted in a 283.7 ± 14.7 - fold increase of viable CD45⁺CD34⁺CD38⁻CD45RA⁻ HPCs within 11 days¹⁵. The limitations of UCB in terms of its low blood cell count, which prevented the achievement of the most optimal outcomes in patients post-HSCT, can now be overcome by HSPC expansion through culturing with various substances. In fact, several studies

have reported large increases in the number of HSPCs, and subsequent improved outcomes in patients.

Other indications for HSPC expansion

Besides the expansion of HSPCs from UCB, HSPCs derived from the BM and PB can also be expanded to improve the outcomes of HSCTs. Regardless of the source of HSCs, the success of HSCT is affected by the number of transplanted cells. A sufficiently large number of HSCs must be transplanted for HSCT to succeed^{17, 18}. Thus, HSPC expansion techniques can also be useful when the number of cells obtained from BM or PB stem cell harvest is insufficient for HSCTs, or when insufficient hematopoietic progenitor cells are mobilized

Table 2. Summary of several clinical trials using cell selection in haploidentical HSCT

Study	Patient group	No. of patients	GvHD rates	Outcome
R. Mitchell <i>et al.</i> [26]	TCR $\alpha\beta$ + /CD19+ cell-depleted recipients HSCT	20	20% for grades II-IV aGvHD with 0% grade III-IV aGvHD seen	All patients achieved primary neutrophil and platelet engraftment and 80% OS rate at 5 years
D. Balashov <i>et al.</i> [28]	TCR $\alpha\beta$ + /CD19+ depleted graft recipients	37	7 patients with grade II aGvHD, 1 patient with grade IV aGvHD	94.6% neutrophil engraftment rate
M.A. Diaz <i>et al.</i> [30]	CD45RA-depleted graft recipients	20	1 patient with grade I aGvHD, 1 patient with moderate cGvHD	All patients grafted, with early and rapid immune reconstitution in all lymphocyte subsets
B. M. Triplett <i>et al.</i> [31]	Trial 2 CD3-depleted progenitor cell product recipients	31	7 patients with grade III-IV aGvHD	Median T-cell count of 10 T cells/ μ L at day +30
	Trial 2 CD45RA-depleted progenitor cell product recipients	26	6 patients with grade III-IV aGvHD	Median T-cell count of 550 T cells/ μ L at day +30
F. Touzot <i>et al.</i> [32]	CD45RA-depleted allograft recipients	5	1 patient with grade I GvHD	Engraftment in 4 of 5 patients, cellular and humoral immunity re-established within a year of HSCT
D. R. Shook <i>et al.</i> [33]	Patients who all received 1 CD3-depleted cell product and 1 CD45RA-depleted cell product	8	0%	Median CD34 recovery 59.2% with CD45RA depletion, 82.4% with CD3 depletion. All engrafted within 14 days, rapidly achieved 100% donor chimerism
M. Bleakley <i>et al.</i> [34]	Recipients of CD34-selected PB stem cell grafts with a defined dose of memory T cells purged of CD45RA+ naive T cells	35	23 patients developed grades II-IV aGvHD, 3 patients developed cGvHD	All patients had neutrophil engraftment. DFS rate of 77% at 1 year, 70% at 2 years
E. Rådestad <i>et al.</i> [35]	$\alpha\beta$ T cell-depleted HSCT recipients	27	11 out of 12 patients developed aGvHD during treatment, but only 3 developed their max grade post-infusion (1 grade I aGvHD, 2 grade II aGvHD)	10 out of 12 patients alive at 12 months
D. A. Shasheleva <i>et al.</i> [36]	TCR $\alpha\beta$ /CD19 cell-depleted HSCT recipients	5	1 patient with grade I aGvHD	Full donor myeloid chimerism established in all patients, all patients alive at 4 years (median). Immune reconstitution was delayed with no severe infections.

TCR, T cell receptor; PB, peripheral blood

into the bloodstream. Hence, there is potential for the expansion of HSPCs to achieve an adequately large number of cells for a successful transplant^{19, 20}. Another possible use for HSPC expansion that is becoming increasingly relevant is in gene therapy, since after the HSCs have been genetically modified, the number of genetically modified cells may be low. Thus HSPC expansion is needed to achieve the minimum cell dose before the transplant can occur^{21, 22}. In addition, HSCT and chemotherapy are often followed by a period of neutropenia in which faster neutrophil recovery results in better outcomes for the patient²³. Therefore, HSPC expansion has also been explored as a potential treatment to reduce the period of neutropenia after HSCT and chemotherapy, enhancing neutrophil recovery and reducing the chances of infections^{10, 12, 23}.

Cell Selection

Haploidentical transplantation (Table 2)

To overcome the risk of GvHD due to T cell alloreactivity with haploidentical transplantations, there is a

need for *in vitro* or *in vivo* T cell depletion. However, these processes could also blunt the effect of GVT. Thus, there is a need for research exploring how to maximize the anti-leukemic effects of the graft while removing the GvHD effect of transplanted cells²⁴. One of the current methods for haploidentical transplantation is TCR $\alpha\beta$ + /CD19+ cell depletion, in which there is a selective depletion of T cells expressing the $\alpha\beta$ T cell receptor (TCR) and CD19+ B cells before transplantation, as these cells are responsible for GvHD²⁵⁻²⁷. However, T cells expressing $\gamma\delta$ TCR are retained as $\gamma\delta$ T cells are able to produce the GVT effect without causing GvHD^{25, 27}. In one study, thirty-seven patients with primary immunodeficiency (PID) received transplants from a matched unrelated donor (MUD) or haploidentical mismatched related donor (MMRD), with all grafts being TCR $\alpha\beta$ + /CD19+ depleted²⁸. Patients received a median of 11.7×10^6 /kg CD34+ cells and 10.6×10^3 /kg TCR $\alpha\beta$ + cells. As a result, neutrophil engraftment occurred in 35 of 37 patients 11 – 28 days after transplantation, with grade II GvHD occurring in only 7 cases and grade IV GvHD occurring in 1 case, corre-

sponding to a 21.5% probability of grade II GvHD and 2.8% probability of grade IV GvHD²⁸. With TCR $\alpha\beta$ + / CD19+ cell depletion, the GvHD probability and severity can be maintained at a moderate level. Together with TCR $\alpha\beta$ + / CD19+ cell depletion, another method currently used to lower GvHD rates and increase survival rates in haploidentical transplants involves the depletion of naïve CD45RA+ cells while retaining memory CD45RO+ cells²⁹⁻³¹. Naïve CD45RA+ cells are selectively depleted, as they can lead to GvHD, while memory CD45RO+ cells are retained, as they can help to protect the body against infections, thereby maintaining the GVT effect without causing GvHD²⁹⁻³¹. In one clinical study, 41 patients received CD3-depleted (CD3-dep recipients) progenitor cell products (HPC,A) and 26 received CD45RA-depleted HPC,A (CD45-dep recipients)³¹. The results showed faster T cell recovery in CD45RA-dep recipients, with a median T cell count of 550 T cells/ μ L after 30 days compared to only 10 T cells/ μ L in the CD3-dep recipients. Furthermore, quantitative B cell recovery occurred earlier in CD45RA-dep recipients, while NK cell recovery was quantitatively higher in CD3-dep recipients³¹. For CD3-dep recipients, there were two consecutive trials. In trial 1, six out of the ten patients had acute GvHD (aGvHD) grade III-IV, while in trial 2, seven out of 31 patients had aGvHD grade III-IV. Furthermore, for CD45RA-dep recipients, six out of 26 had aGvHD grade III-IV³¹. The results of this study also showed that 76% of CD3-dep recipients had detectable viremia in the first 180 days post-transplant, compared to only 35% of CD45RA-dep-recipients. In addition, 58% of the viremic CD3-dep-recipients had prolonged viremia compared to only 11% of the viremic CD45RA-dep-recipient³¹. Thus, both CD45RA-dep recipients and CD3-dep recipients had similar GvHD rates, indicating that both the depletion of CD45RA cells and CD3 cells can maintain GvHD rates at a moderate level. However, CD45RA depletion is the optimal treatment option, as it results in a faster immune reconstitution and allows for the preservation of immunity against viruses, leaving transplant recipients less susceptible to viral infections^{30, 32}.

Immune Regulatory Cells

Mesenchymal stromal cells (MSC) (Table 3)

MSCs are multipotent spindle-shaped plastic-adherent cells isolated from the BM, adipose, and other tissue sources³⁷, which can differentiate into cells of several lineages³⁸. Due to the ability of MSCs to interact with both the innate and adaptive immune systems, exhibiting a strong immunosuppressive activity on both immune systems and inducing tolerance, many studies have explored the role of MSCs in tissue repair, im-

mune modulation, and the BM microenvironment, and hence the potential of MSCs in clinical treatment for various conditions³⁸⁻⁴⁰. One of the conditions that is frequently studied is aplastic anemia (AA), which is a BM failure disorder characterized by marrow hypoplasia and peripheral pancytopenia, which is the reduction in the number of red blood cells (RBCs), white blood cells (WBCs), and platelets (PLTs)^{41, 42}. In a study using animal models, irradiation was used to induce BM failure in the animals, since HSPCs and committed BM progenitor cells are more sensitive to irradiation⁴¹. Mice were administered 1×10^6 lymph node cells to induce acquired AA, mimicking AA in humans⁴¹. Subsequently, 1×10^6 to 2.5×10^7 MSCs were transplanted into each mouse, and preclinical studies reported an increase in the levels of WBCs, PLTs, and hemoglobin in PB after MSC transplantation compared to the control group, which did not receive MSC transplantation. The group that received MSC transplantation also showed BM recovery and an increase in the number of BM cells *in vivo*, as well as an increase in cytokines FLT3LG and TGF-beta 1 secreted by MSCs, which are involved in the proliferation and differentiation of HSPCs⁴¹. In a clinical trial, six patients with severe AA (SAA) received an MSC transplant, and two had a hematopoietic recovery in both BM and PB three months after transplantation; however, some patients manifested adverse events during or after MSC infusions⁴¹. Thus, while MSCs have great potential in the treatment of AA, more research and studies are needed to develop an MSC-based treatment that can avoid the adverse events in most, if not all, patients receiving MSC transplantation. Other than AA, studies have also shown the ability of MSCs to prevent or treat GvHD associated with HCST⁴³⁻⁴⁷. A study of 22 patients with refractory GvHD was conducted, with a median dose of infused MSCs of 1.64×10^6 cells/kg, and a total of 79 MSC infusions administered⁴³. The patients' response to MSC infusions was evaluated in terms of no response (NR), which corresponds to no change in GvHD grade, partial response (PR), which corresponds to at least 1 grade decrease in GvHD compared with the patient's initial condition on day 0, and complete response (CR), which corresponds to an absence of GvHD signs. After MSC therapy, the overall response rate was 79.1% for 19 of the patients, with 11 patients achieving CR and 8 patients achieving PR. Among these, 7 out of the 11 CR patients initially only achieved PR after induction therapy but were able to achieve CR after additional MSC therapy⁴³. In addition, the survival rate in patients at 6 months was significantly higher in the CR and PR groups, with a survival rate of 76.5%, compared to the NR group, which had a much lower survival rate of 20%⁴³. These results indicate the effectiveness of MSC therapy in reducing

Table 3. Summary of several clinical trials using MSC-based therapy

Study	Patient group	No. of patients	Outcome
V. F. Gonzaga <i>et al.</i> [41]	AA patients treated with transplant of MSCs	6	2 patients (33.3%) with hematopoietic recovery in BM and PB 3 months after transplant
M. Cetin <i>et al.</i> [43]	Refractory GvHD patients given MSC therapy	22	79.1% overall response rate (45.8% CR, 33.3% PR). 63.6% survival rate at 6 months.
U. Salmenniemi <i>et al.</i> [44]	Refractory GvHD patients treated with third party BM-derived, platelet-lysate-expanded MSCs	30	62% of aGvHD patients showed a response at day 28 after MSC therapy. 42% of patients alive at 767 days.
G.M. Dotoli <i>et al.</i> [46]	aGvHD patients treated with infusion of MSCs	46	50% of patients presented clinical improvement (3 CR, 14 PR, 6 transient PR). 17.4% estimated probability of survival at 2 years.
Z. Liu <i>et al.</i> [47]	SAA patients that received haplo-HSCT co-transplanted with MSCs	44	40 patients (91%) achieved myeloid recovery and full donor chimerism. 23 patients (52%) developed aGvHD (11 with grade I, 10 with grade II, 2 with grade III). 6 patients (14%) developed cGvHD. 77.3% OS rate.
X. Wang <i>et al.</i> [59]	Control group	25	8 cases of grade I aGvHD, 4 cases of grade II aGvHD, 5 cases of grade III and above aGvHD. 1-year and 2-year OS rates of 52.6% and 41%.
	Recipients of MSC infusion	25	15 cases of grade I aGvHD, 3 cases of grade II aGvHD. 1-year and 2-year OS rates of 67.4% and 48.1%. Shorter platelet engraftment time than control group.
Y. Pang <i>et al.</i> [50]	AA patients treated with infusion of allogeneic BM-MSCs	74	28.4% overall response rate (6.8% CR, 21.6% PR). 87.8% OS rate at 17 months.

AA, Aplastic anemia; BM, bone marrow; SAA, Severe aplastic anemia; CR, complete response; PR, partial response

or completely treating GvHD in a significant number of patients. Additional MSC therapy after an initial induction therapy can further improve the outcomes of patients. Another study assessed the feasibility of an MSC-derived 2-factor combination (2FC) of CXCL5 and anti-CCL24 in place of MSCs in the treatment of GvHD⁴⁸. In this study, GvHD mouse models were produced via the tail vein injection of human PB mononuclear cells (PBMCs) into NSG mice, followed by Cesium^{1, 37} irradiation in mice 3 to 4h before PBMC transplantation⁴⁸. The 2FC treatment was administered to the mice 10, 14, 17, and 21 days post-PBMC transplantation, while the extended treatment with reduced dosage was administered 4, 7, 11, 18, 21, 25, and 28 days post-transplantation⁴⁸. The results showed that by day 36, survival in mice with moderate GvHD administered 2FC treatment was higher at 81.0% with mild symptoms compared to 50.0% in the control group administered Dulbecco's Phosphate-Buffered Saline (DPBS) with moderate symptoms⁴⁸. The immunosuppressive effect of 2FC therapy was similar to that of BM-MSC treatment and superior to the cyclosporine A (CsA) treatment⁴⁸. For mice with severe GvHD, the mice that received the 2FC treatment had higher survival rates compared to the DPBS control group, while the BM-MSC and CsA treatment did not lead to much improvement, and hence had similar survival rates to the control group and lower survival rates than the 2FC therapy group⁴⁸. Although further clinical trials are required to assess the feasibility of the 2FC treatment for GvHD in humans, the results of the study show that 2FC has great potential in the treatment of GvHD and could

even be more effective than MSC therapy.

Regulatory T (Treg) cells

Treg cells have also been explored as a potential treatment to improve the outcomes of HSCTs by treating or preventing GvHD. However, a significant limitation of Treg cells treatment is that they suppress anti-tumor immunity, thereby inhibiting cancer treatment⁵¹⁻⁵⁶. Treg cells are a type of CD4+ T cells that express the transcription factor Forkhead box P3 (FoxP3) and are involved in the suppression of immune responses against both self- and non-self - antigens. As a result, they are able to ameliorate GvHD, but also worsen the prognosis of cancer patients^{53, 56}. In one of the studies conducted, Tregs were isolated from a unit of UCB matched to the patient, and a total of 11 patients were treated⁵⁷. Among these, 2 patients were treated at 3×10^6 Treg/kg, 4 were treated at 10×10^6 Treg/kg, 1 was treated at 30×10^6 Treg/kg, and 4 were treated at the highest achievable dose of 100×10^6 Treg/kg⁵⁷. In addition, there were a total of 22 control patients⁵⁷. The results showed that for the 11 patients treated with Tregs, the CI of grade II-IV aGvHD at 100 days was 9%, which was much lower than the control group that had a CI of grade II-IV aGvHD of 45% and grade III-IV of 27%. Furthermore, chronic GvHD (cGvHD) developed in 3 out of the 22 patients in the control group, while none of the Treg recipients developed cGvHD⁵⁷. Another study harvested intestinal tissue from mice; the intestine is the most common tissue involved in GvHD after HSCT. The results showed that the intestinal injury was significantly attenuated in mice that received

Table 4. Summary of several clinical trials using DLI

Study	Patient group	No. of patients	GvHD rates	Outcome
A. Liou <i>et al.</i> [59]	Recipients of DLI	35	22% developed aGvHD, cGvHD or mixed aGvHD and cGvHD after DLI.	71.4% event-free survival (EFS) rate.
V. V. Swaminathan <i>et al.</i> [60]	Recipients of DLI	58	40% developed GvHD	59.6% of patients achieved 100% chimerism, 28.4% achieved mixed chimerism. 81.1% OS rate.
J. K. Davies <i>et al.</i> [61]	Recipients of alloanergized DLI	16	31.3% developed aGvHD, 25% developed cGvHD.	OS rate of 38% at 1 year.
C. H. Yan <i>et al.</i> [63]	Recipients of prophylactic DLI followed by minimal residual disease (MRD) test and GvHD-guided multiple DLIs	100	43% developed at least grade I aGvHD. 66% developed cGvHD.	3-year CI of relapse, leukemia-free survival and survival post-transplant were 32.4%, 50.3%, and 51.4% respectively.
S. Nikiforow <i>et al.</i> [64]	Recipients of CD25/Treg cell-depleted DLI at dose level 1	6	33.3% developed cGvHD	0% response rate.
	Recipients of CD25/Treg cell-depleted DLI at dose level 2	15	20% developed aGvHD. 26.7% developed cGvHD.	Overall response rate of 60%. 1-year EFS rate of 27%. 1-year CI rate of relapse was 67%.
	Recipients of unmanipulated DLI	14	0%	Overall response rate of 14%. 1-year EFS rate of 0%. 1-year CI rate of relapse was 100%.
X. N. Gao <i>et al.</i> [65]	Recipients of prophylactic DLI	31	58.1% developed grade I-IV aGvHD after DLI. 38.7% developed cGvHD.	9 patients (29.0%) relapsed at a median of 87 days after DLI and 209 days after HSCT. Estimated OS rates of 58.5% at 1 year and 40.1% at 2 years from HSCT.
F. Kerbage <i>et al.</i> [66]	Recipients of DLI	64	Less than 10%.	Response rates of more than 60%.
M. Merker <i>et al.</i> [67]	Recipients of DLI	55	35% developed aGvHD.	6-month OS of 57%. 6-month cumulative incidence of relapse (CIR) of 55%.
	Recipients of cytokine-induced killer cell therapy	36	25% developed aGvHD.	6-month OS of 77%. 6-month CIR of 22%.

DLI, Donor lymphocyte infusion

CD150+ Treg cells, and the number of infiltrated leukocyte common antigen lymphocytes was reduced significantly compared to the control group⁵². These results indicate the potential for Treg treatment to be used to prevent the development of GvHD in post-HSCT patients. However, the ability of Tregs to support tumor progression and suppress anti-tumor immunity means that further research is needed to develop a safer Treg treatment⁵¹.

Immune Effector Cell Therapy

Donor lymphocyte infusions (DLI) (Table 4)

While HSCT remains the only curative treatment for several diseases, such as leukemia, many transplant recipients still do not survive post-transplant due to relapse^{58, 59}. When a patient relapses, one of the treatment methods used is DLI, in which T lymphocytes from the donor are used to induce the GVT effect in patients⁶⁰. However, while DLI has been shown to produce benefits through the induction of the GVT effect, it often leads to GvHD after infusions⁶¹⁻⁶³. In a study on the safety and effectiveness of DLI in children, DLI was performed in 58 children, of whom 71% had benign

hematological conditions and 29% had relapsed or high-risk leukemia/lymphoma⁶⁰. In this study, 28 children received single DLI, 17 children received two DLI, and 13 children received three DLI⁶⁰. As a result, 23 children developed GvHD, with an overall survival (OS) rate of 81.1%⁶⁰. In another study, 21 patients received a CD25/Treg-depleted DLI, a single infusion of fresh cells immediately following selection, resulting in one case of Grade III aGvHD, two cases of grade I aGvHD, and six cases of cGvHD⁶⁴. Thus, DLI has indeed been associated with higher rates of GvHD. Therefore, there is a need to investigate further methods for the treatment of relapses that are able to induce the GVT effect without causing GvHD.

Chimeric antigen receptor (CAR) T cells (Table 5)

CAR T cells are T cells that are engineered to express CARs, which target the B-cell-specific antigen CD19, as CD19 is expressed at high and stable levels in the tumor tissue of most patients with B-cell-acute lymphoblastic leukemia (B-ALL), non-Hodgkin's lymphoma (NHL), and chronic lymphocytic leukemia (CLL). This allows the CAR T cells to be used in the treatment of these B cell cancers⁶⁸⁻⁷⁰. In a global study

Table 5. Summary of several clinical trials using CAR T cell therapy

Study	Patient group	No. of patients	Outcome
S. L. Maude <i>et al.</i> [71]	B-ALL patients that received tisagenlecleucel, an anti-CD19 CAR T-cell therapy	75	Overall remission rate of 81% (61 patients). Rate of relapse-free survival among patients with a response was 80% at 6 months, 59% at 12 months. EFS rate was 73% at 6 months, 50% at 12 months. OS rate of 90% at 6 months, 76% at 12 months after infusion.
X. Wang <i>et al.</i> [73]	Recipients of CD8-enriched T _{CM} cells transduced with a first-generation CD19 CAR	8	5 patients achieved CR or continuing CR, 1 achieved PR and 1 achieved continuing PR. 4 patients were progression-free at 1 and 2 years.
	Recipients of bulk T _{CM} -derived cells (CD8 cells not enriched) transduced with a second-generation CD19 CAR	8	All 8 patients achieved CR or continuing CR. 6 patients were progression-free at 1 year.
H. Jiang <i>et al.</i> [74]	B-ALL patients that received anti-CD19 CAR T-cell therapy	58	51 patients (87.9%) achieved complete remission. 6-month OS rate of 68.9%, 12-month OS rate of 61.1%.
S. J. Schuster <i>et al.</i> [75]	Diffuse large B-cell lymphoma or follicular lymphoma patients that received CD19-directed CAR T cells	28	18 patients (64%) had a response. 6 of 14 patients with diffuse large B-cell lymphoma had complete remission. 10 of 14 patients with follicular lymphoma had complete remission. 57% of patients remained progression-free at 28.6 months.
G. Enblad <i>et al.</i> [76]	B-cell lymphoma or leukemia patients treated with CAR T cells	15	6 patients (40%) had initial CR. 3 of 11 lymphoma patients were in remission at 3 months. 2 patients survived long-term.
K. J. Curran <i>et al.</i> [77]	B-ALL patients given CD19-specific CAR T-cell therapy	24	Overall complete remission/ complete remission with incomplete count recovery rate of 75%. Absence of MRD in 89% of responding patients. 8 patients alive and disease-free after infusion of CAR T cells consolidated with allogeneic-HSCT
C. S. Sauter <i>et al.</i> [78]	B-cell NHL patients given CD19 CAR T cells post-transplant	15	2-year progression-free survival rate of 30%.
F. Ma <i>et al.</i> [79]	B-ALL patients given CD19 CAR-T cell treatment	10	8 patients (80%) reached MRD negative after the 1 st month. For the 8 patients, median OS months was 10.3 months, median EFS months was 4 months.
J. H. Park <i>et al.</i> [80]	B-ALL patients treated with CD19-specific CAR T cells	53	44 patients (83%) had a complete remission. Median EFS was 6.1 months, median OS was 12.9 months.

B-ALL, B-cell-acute lymphoblastic leukemia; **TCM cell, CD8-enriched central memory T cells**

on the use of anti-CD19 CAR T cell therapy tisagenlecleucel for B-ALL, 75 patients received tisagenlecleucel⁷¹. With at least three months of follow-up, the overall remission rate was 81%, with 45 patients having complete remission and 16 having complete remission with incomplete hematologic recovery; the event-free survival (EFS) rate was 73% at 6 months and 50% at 12 months⁷¹. However, all patients with a response to treatment had B-cell aplasia, the median time to B-cell recovery was not reached, and all 75 patients had at least one adverse event during the study, with 95% having an adverse event suspected to be related to tisagenlecleucel⁷¹. While CAR T cell therapy has great potential in the treatment of B-ALL and can lead to high remission and survival rates, the high rates of adverse events indicates that further research is needed to develop a CAR T cell therapy that can maintain high remission and survival rates with lower rates of adverse events⁷². Another study assessed the immunotherapy of NHL in which there were two trials: the first trial (NHL 1) tested CD8-enriched central memory T (T_{CM}) cells transduced with a first-generation CD19 CAR without a costimulatory domain and the second trial (NHL 2) tested bulk T_{CM}-derived cells in which CD8 cells were not enriched, and the bulk T_{CM} cells were

transduced with a second-generation CD19 CAR, including a CD28 costimulatory domain⁷³. For NHL 1, 8 patients received HSCT and CD19 CAR T_{CM} cell infusions. As a result, 5 patients achieved CR or continued CR, 1 patient achieved PR, and 1 achieved continued PR⁷³. For NHL 2, 8 patients received HSCT, and all 8 patients achieved CR or continued CR⁷³. While there were high rates of adverse events with all NHL 1 patients and 7 out of the 8 NHL 2 patients experiencing grade 3 non-hematologic toxicities, these were attributed at the probable or definite level to HSCT⁷³. In addition, there were no grade 2 or higher toxicities attributed at the probable or definitive level to CD19 CAR T_{CM} cell infusions, thereby demonstrating the effectiveness of CD19 CAR T cell therapy for NHL⁷³. Furthermore, CAR T cells persist for long periods of time in the blood, further boosting their effectiveness by making them a long-lasting therapy^{71, 73}. Further research should seek to explore whether CAR T cell therapy can be used as an alternative to HSCTs or in combination with transplants. If they are used together with HSCTs, studies should explore whether CAR T cell therapy should be administered to the patient before or after the transplant.

Table 6. Summary of several clinical trials using NK cell-based therapy

Study	Patient group	No. of patients	Outcome
D. A. Lee <i>et al.</i> [83]	Patients with myeloid malignancies given NK cell infusions	21	5 patients developed a maximum aGvHD of grade 2, 2 patients developed grade 3 aGvHD. 6 patients developed cGvHD. Neutrophil engraftment occurred in 20 patients. Platelet engraftment occurred in 19 patients.
N. Shah <i>et al.</i> [84]	Multiple myeloma patients given UCB-derived NK cells	12	10 patients (83%) achieved a very good PR or better as their best response, including 8 with near CR or better. 6 patients (50%) achieved MRD negativity.
R. Nguyen <i>et al.</i> [85]	AML patients that had chemotherapy and NK cell infusion	21	18 patients (86%) demonstrated transient engraftment with donor NK cells. CI of relapse of 0.393. EFS rate of 60.7 ± 10.9%. OS rate of 84.2 ± 8.5%.
	Control group (AML patients that completed chemotherapy only)	55	CI of relapse of 0.35. EFS rate of 9.1 ± 6.8%. OS rate of 79.1 ± 6.6%.
I. Choi <i>et al.</i> [86]	Refractory acute leukaemia patients given DNKI post HSCT	51	42 patients (82%) achieved initial engraftment. 17 patients (33%) experienced aGvHD, 15 patients (29%) experienced cGvHD. 29 patients (57%) achieved complete remission. Cumulative 3-year EFS rate of 9% and 3-year OS rate of 21%.
S. O. Ciurea <i>et al.</i> [87]	Recipients of mbIL21 expanded donor NK cells	13	All patients achieved primary engraftment, 12 (92%) had 100% donor cell chimerism at day +28 post-transplant. 7 patients (54%) developed grade 2 aGvHD. OS rate of 92% and DFS rate of 85% at 1 year.
	Control group (No NK cell infusion)	45	All patients achieved primary engraftment. 14 patients (31%) developed grade 2-4 aGvHD, 7 patients (16%) developed cGvHD. 25 patients (55.5%) alive at last follow-up.
E. Liu <i>et al.</i> [88]	NHL and CLL patients given anti-CD19 CAR-NK cells	11	8 patients (73%) had a response, with 7 patients who had a complete remission.
B. C. Shaffer <i>et al.</i> [93]	AML and MDS patients treated with NK cell infusion	8	3 patients (37.5%) achieved responses. No GvHD after NK infusion.
R. Romee <i>et al.</i> [94]	AML patients given infusion of memory-like NK cells	9	5 patients (55%) had a response, with 4 (45%) achieving complete remission.
V. Bachanova <i>et al.</i> [95]	NHL patients given NK cells	15	4 patients (26.6%) had a response (2 CR, 2 PR) at 2 months. No GvHD after NK infusion.

AML, Acute myeloid leukemia; DNKI, Donor NK cell infusion; mbIL21, Membrane-bound interleukin 21; NHL, Non-Hodgkin's lymphoma; CLL, Chronic lymphocytic leukemia; MDS, Myelodysplastic syndrome

Natural killer (NK) cells

NK cells are part of the innate immune system. They kill virus-infected cells and cancerous cells without requiring prior exposure or sensitization to these cells, thereby allowing them to contribute to the GVT effect. Thus, several studies have explored the use of NK cell-based immunotherapy to improve the outcomes of patients⁸¹⁻⁸⁴. In a phase II clinical trial, 21 children with acute myeloid leukemia (AML) received NK cell therapy with a median of 12.5×10^6 NK cells/kg⁸⁵. Although 20 of the 21 patients treated developed grade ≥ 3 neutropenia, and 5 patients developed grade ≥ 3 thrombocytopenia, 20 of the 21 patients had absolute neutrophil and platelet count recovery within 45 days after NK cell infusion and none had opportunistic infections, notable bleeding, or GvHD⁸⁵. However, the results also showed that NK cell infusion did not improve the CI of relapse or OS compared to chemotherapy alone⁸⁵. In another study, 51 patients with refractory acute leukemia received HSCT followed by at least one donor NK cell infusion (DNKI)⁸⁶. Among the 51 patients, 24 received all four planned doses of DNKI, while 27 did not receive one or more of the planned doses of DNKI due to cytokine release syndrome, rapid leukemia progression, inadequate NK cell product and CD3+ cells >

10%, transient mental change, sepsis, or patient refusal⁸⁶. The results showed that 42 recipients achieved initial engraftment with an absolute neutrophil counts (ANC) $\geq 500/\mu\text{L}$ at a median of 15 days after HSCT, and 18 patients achieved platelet counts $\geq 20,000/\mu\text{L}$ at a median of 32 days⁸⁶. However, 17 patients experienced aGvHD at a median of 1.1 months after HSCT, while 15 patients developed cGvHD at a median of 3.4 months after HSCT⁸⁶. Of the 51 patients who received at least 1 DNKI, 29 achieved complete remission, and the cumulative 3-year EFS rate was 9%, while the 3-year OS rate was 21%⁸⁶. In another phase I clinical trial, 13 patients with high-risk AML, myelodysplastic syndrome (MDS), or chronic myeloid leukemia (CML) received membrane-bound interleukin 21 (mbIL21) NK cell infusions⁸⁷. Primary engraftment was achieved in all 13 patients, with 12 of 13 patients having 100% donor cell chimerism after day 28 post-HSCT⁸⁷. The median time to neutrophil engraftment was 19 days, while the time to platelet engraftment was 22 days⁸⁷. However, 7 patients developed grade 2 aGvHD, with no grade 3-4 aGvHD nor cGvHD. Furthermore, the one-year OS rate was 92% while the one-year disease-free survival rate was 85%⁸⁷. For the control group (45 patients), all patients achieved primary engraftment, with a median

time to neutrophil and platelet engraftment of 18 and 40 days. Among these, 14 patients developed grade 2-4 aGvHD, while 7 patients developed cGvHD, with 25 patients alive at the last follow-up⁸⁷. While NK cell-based immunotherapy is generally safe, toxicities can develop after treatment. However, at present, the effectiveness of NK cell infusions in the treatment of patients is not very significant, and further research is needed to develop a more effective NK cell-based therapy. In a study in which NK cells were engineered to express CAR (CAR-NK cells), 9 patients received a CAR-NK product that was partially matched with the HLA genotype of the recipient, while two patients received a CAR-NK product that did not take HLA matching into consideration⁸⁸. As a result, at a median follow-up of 13.8 months, 8 patients had an objective response to the treatment that occurred during the first month after infusion⁸⁸. Seven patients had CR and one patient showed a complete remission of high-grade lymphoma⁸⁸. With a high response rate and fewer toxicities, this study shows the potential effectiveness and safety of CAR-NK cell infusions in treating patients despite the CAR-NK products being HLA mismatched. Other studies have shown the possibility of producing several doses of CAR NK cells from a single unit of UCB⁸⁹. Thus, future studies could seek to explore the possibility of making CAR-NK cell infusion a more accessible, universal treatment, since the use of CAR-NK cells could eliminate the need for infused cells to be specific to individual patients. The role of NK cells in cancer treatment has also been explored in anti-tumor monoclonal antibody (mAb) therapies, since one of the mechanisms by which the mAbs target tumor cells is antibody-dependent cell-mediated cytotoxicity (ADCC), which is mediated by NK cells^{90, 91}. The binding of IgG antibodies to the target tumor cells allows for the recruitment of NK cells to the tumor cells via the binding of NK cells' fragment crystallizable receptor (FcR), CD 16A, to IgG, thus aiding the NK cells in mediating ADCC to kill tumour cells^{90, 91}. One of the most widely used mAbs, which was also the first mAb therapy used for cancer treatment, is rituximab, which is an IgG1 mAb that targets CD20, a B cell differentiation antigen^{90, 91}. In a study conducted using rituximab, 101 patients with follicular lymphoma were treated with rituximab-containing antibody combinations⁹². Among these, 46 patients were administered rituximab with galiximab and 55 were administered rituximab with epratuzumab⁹². Unlicensed NK cells lack the expression of an inhibitory killer immunoglobulin-like receptor (KIR) for self-HLA class I ligands, and are less responsive than licensed NK cells in steady state; however, they can elicit strong responses in inflammatory conditions⁹². The results of this study showed that coating tu-

mor cells with rituximab allows for the hypo-responsive unlicensed NK cells to be activated and to mediate increased cytotoxicity, contributing to a greater response against the tumor cells by the NK cell repertoire⁹². Thus, there is great potential for the use of anti-tumor mAb therapies to enhance ADCC by NK cells, and future research should explore other methods of boosting NK cells' responsiveness to tumor cells and mediation of ADCC (**Table 6**).

Gamma delta ($\gamma\delta$) T cells

There is an increasing amount of research on the potential use of $\gamma\delta$ T cells in the treatment of cancer. These cells are not restricted by the need for antigen presentation by major histocompatibility complex (MHC) molecules and are able to produce abundant cytokines, playing a part in both innate and adaptive immunity against tumours⁹⁶⁻⁹⁸. In a study using mice, nude mice were injected intravenously with Daudi cells from the Daudi human tumor cell line⁹⁹. Three days later, the mice were injected with $\gamma\delta$ T cells plus rhIL-2, rhIL-2, or phosphate-buffered saline (PBS). Then, IL-2 was administered on the day of cell transfer, with treatment continuing twice each day for 4 days⁹⁹. The results showed that the *ex vivo*-expanded $\gamma\delta$ T cells showed potent cytotoxicity against all of the tested lymphoma cell lines, and the survival rate and change in body weight of mice treated with $\gamma\delta$ T cells plus IL-2 was significantly higher than that of the PBS or IL-2-treated group⁹⁹. Furthermore, no lymphoma cells were found in the BM smears from mice in the $\gamma\delta$ T cells plus IL-2 treatment group, while two IL-2-treated mice had 7% and 8% of lymphoma cells in the BM smears, with a percentage that was even higher for two PBS-treated mice (21% and 24%)⁹⁹. In another study, four patients with advanced refractory hematological malignancies who were not eligible for allogeneic transplantation received an infusion of a CD4/CD8 T cell-depleted leukapheresis product and Hi-Cy/Flu product as prior immunosuppressive chemotherapy, together with an infusion of an average of $2.17 \times 10^6/\text{kg}$ $\gamma\delta$ T cells with < 1% CD4- or CD8-positive cells remaining in the product¹⁰⁰. The duration of neutropenia was 20 days. Three out of the 4 patients achieved complete remission, which lasted between 2 and 8 months, while the fourth patient died from severe septicemia after day 45¹⁰⁰. However, this patient's hematopoiesis had already recovered, and none of the patients showed any signs of acute or cGvHD nor organ injury¹⁰⁰. Although $\gamma\delta$ T cells have yet to be widely studied, they have shown potential for use in treatment, and subsequent research should aim to explore the safety and efficacy of $\gamma\delta$ T cell-based immunotherapy further.

Conclusion and Future Perspectives

The importance of HSCTs in the treatment of various conditions is undeniable. However, there are several limitations of HSCTs that are worth mentioning, particularly in terms of the quantity and quality of transplanted cells and toxicity, which could lower the effectiveness of transplants in the treatment of patients. The latter could result in the need for the use of cellular engineering. In fact, several cellular engineering methods have been used to date, including UCB expansion, cell selection, infusion of immune regulatory cells, including MSCs and Tregs, and immune effector cell therapy, which includes DLIs, CAR T cells, NK cells, and $\gamma\delta$ T cells. UCB expansion has been mostly successful, with several of the molecules used causing large increases in the number of HSPCs and improved outcomes in patients^{10, 12, 13, 15}. In haploidentical transplantations, two cell selection methods are TCR $\alpha\beta$ + /CD19+ cell depletion and naïve CD45RA+ cell depletion, both of which have been shown to contribute to a lower GvHD rate in patients^{28, 31}. The use of MSCs in animal trials has led to better outcomes in mice, while the use of MSCs in patients has led to some improvements; however, treatment in humans has also led to adverse events. Thus, further research is needed to develop safer MSC therapies associated with fewer adverse events^{41, 43, 48}. The use of Tregs has also shown potential in lowering the rates of GvHD, but can also contribute to tumor progression while suppressing anti-tumor immunity. Thus, Tregs are not a very safe treatment option^{51, 52, 57}. With the use of DLIs being associated with higher rates of GvHD, other immune effector cell therapies have been explored to induce GVT effects without high GvHD rates⁶¹⁻⁶⁴. Among these, CAR T cell therapy has shown great potential in leading to higher remission and survival rates; however, several recipients have been reported to also experience adverse events^{71, 73}. Thus, CAR T cell therapy may require some modifications to lower the rates of adverse events. Research should seek to determine the optimal way to use CAR T cells, namely whether they should be used together with or instead of HSCTs, as well as the optimal conditions for their use. While the use of NK cells is mostly safe, their use has not led to significant improvements in patient outcomes⁸⁵⁻⁸⁷. However, CAR-NK cells have shown some effectiveness in improving remission rates despite the lack of HLA matching, and the use of anti-tumor mAbs, such as rituximab, has been shown to help activate unlicensed NK cells, as well as increase their cytotoxicity^{88, 92}. Thus, NK cells show great potential for use in these therapies. Finally, the use of $\gamma\delta$ T cells is a more novel and less widely studied area of research that could be a potent therapy in the treatment of cancer; however,

more studies are needed to confirm its safety and effectiveness^{99, 100}.

Future research should seek to evaluate and modify cellular engineering methods to improve their safety and effectiveness in the treatment of patients. In addition, studies should also seek to explore ways in which to use genetic engineering to reduce the allogeneicity of the cells used in transplants, as well as lower the costs and improve the efficiency of the processes. As a result, universal donors and off-the-shelf therapy can be made more readily available and treatments more affordable for patients.

Ethics Approval and Consent to Participate

Not applicable

Consent for Publication

Not applicable

Availability of Data and Materials

Data sharing is not applicable to this article as no new data were generated or analyzed in this study.

Authors' Contributions

WYKH conceived the idea for the article, and KVQYS prepared the original draft of the manuscript. WYKH and KVQYS were both involved in performing the literature search and data analysis, as well as reviewing and editing the manuscript. Both authors have read and approved the manuscript.

Conflicts of Interest

The authors declare no conflict of interest. Disclosure forms provided by the authors are available on the website.

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