Review article

Epstein–Barr virus–associated cellular immunotherapy

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A B S T R A C T

Epstein–Barr virus (EBV) is a human herpes virus that is saliva-transmissible and universally asymptomatic. It has been confirmed that more than 90% of the population is latently infected with EBV for life. EBV can cause a variety of related cancers, such as nasopharyngeal carcinoma, diffuse large B-cell lymphoma, and Burkitt lymphoma. Currently, many clinical studies have demonstrated that EBV-specific cytotoxic T lymphocytes and other cell therapies can be safely and effectively transfused to prevent and treat some diseases caused by EBV. This review will mainly focus on discussing EBV-specific cytotoxic T lymphocytes and will touch on therapeutic EBV vaccines and chimeric antigen receptor T-cell therapy briefly.

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Introduction

Epstein–Barr virus (EBV) is a human herpes virus that is saliva-transmissible and universally asymptomatic. It was first isolated from B-cell lymphoma in 1964 [1]. The viral activity phase positive rate of EBV-DNA in children is 11.5% [2]. EBV infects more than 95% of adults and establishes a lifelong infection [3]. EBV seroprevalence may be associated with socioeconomic and racial/ethnic differences [4]. EBV has linked to infectious mononucleosis (IM), nasopharyngeal carcinoma (NPC), Burkitt lymphoma, gastric cancer, multiple sclerosis (MS) and other multiple diseases [5–9]. Patients undergoing solid-organ transplantation or hematopoietic stem cell transplantation (HSCT) may be at risk for posttransplant lymphoproliferative disorders (PTLDs) and even death due to reactivation of EBV [10–12].

In a healthy body, the immune system can efficiently identify and remove most other viruses and harmful tumor cells by recognizing antigenic substances and activating lymphocytes to protect the host. However, in some cases, EBV can escape the body’s immune surveillance, causing a variety of serious diseases [13]. The cytotoxic T lymphocytes (CTLs) are one of the major effector cells in the acquired immune system and have high specificity and killing capacity. CTL-killing is a highly sensitive and rapid process that kills target cells directly. EBV-CTL cellular immunotherapy has been applied in the treatment of diseases caused by EBV. Encouraged by the striking results of chimeric antigen receptor (CAR) T cells therapy targeting B-cell antigens, CAR-T cell therapy targeting EBV antigens is also under development.

Epstein–Barr Virus

EBV is a double-stranded DNA virus. It was the first tumor-related DNA virus found in humans [14]. Similar to other herpesviruses, EBV has a characteristic three-layered configuration: an outer lipid bilayer envelope with viral glycoproteins responsible for recognizing and membrane fusion, the inner pseudocapsid nucleocapsid with a 172-kb double-strand DNA genome and an intermediate pleomorphic episomal compartment with 20–40 different viral proteins [15]. EBV has high variability, and different variants have distinct pathogenicity and regional distribution [16]. The genes encoding the latent membrane protein (LMP) LMP1, EBV nuclear antigen (EBNA) EBNA2 and EBNA3 protein families were found to be the largest number of variants in the EBV genome, followed by BDLF3, which encodes glycoprotein gp150, BLLF1, which encodes gp350/220, BLF21, and BRF2 [17].

There are two cycles of EBV infection in the host: the lytic and latent periods. During primary infection, EBV can drive the activation and expansion of B lymphoblastoid cells so that EBV can be latently present in B-cell populations. Primary EBV infection mainly occurs in the oral cavity, and it replicates in epithelial cells. It is a complicated
and multistep process to infect epithelial cells. EBV uses its glycoproteins to bind to the surface receptor of host cells (Figure 1). EBV attaches to the B-cell surface by binding to CD21 via the envelope glycoprotein gp350/220. Under certain circumstances, EBV binding to cells can induce the signaling pathway to enter the activated state. Subsequently, the viral membrane fuses with the host membrane. Then, the viral capsid passes through the cytoplasm and is transported to the host cell's nucleus. Finally, the virus is released into the nucleus through nuclear pores for replication and proliferation [18].

When a person is infected with EBV for the first time, if EBV invades the body through blood and lymph, EBV will continue to replicate in cells, causing cell destruction and viruses release. This situation is likely to cause IM [19]. If cells are not destroyed, EBV will be latent in the body. EBV can induce tumors in the body through many mechanisms. EBNA and LMPs accelerate the transformation of B lymphocytes [20]. EBNA regulates cells from many aspects, such as gene expression, gene maintenance and cell-cycle regulation [21–24]. LMP1 is a malignant transformation gene of EBV [25]. LMP1 mediates tumorigenesis by inhibiting cell differentiation and apoptosis, inducing cell proliferation, immortalization and transformation, as well as mediating metastasis of tumor cells [26–28]. When human immunity is compromised, EBV will be activated massively and may cause a variety of diseases. Latent EBV infection is classified into stages I, II, III and 0. The disease associated with latent stage I is Burkitt lymphoma. There are some diseases related to latent phase 2, such as Hodgkin lymphoma (HL), natural killer (NK)/T-cell lymphoma, diffuse large B-cell lymphoma (DLBCL), NPC and gastric cancer. Diseases related to latent stage III include immunoblastic lymphoma and PTLD in immunosuppressed people [20].

EBV can evade the immune system and remain hidden in the human body for a long time [29]. EBV mainly interferes with the body's immunity through the following mechanisms: (i) dampening of innate immunity: by inhibiting Toll-like receptors, nuclear factor kappa B (NF-kB) and other signaling pathways, the body's innate immune system is weakened; (ii) downregulation of latent EBV gene expression: blocking or restricting the expression of EBV genes so that the body's immune system cannot distinguish EBV; (iii) interference with the cellular immune response: EBV can inhibit effective antigens presentation by inhibiting major histocompatibility complex (MHC)–in addition, the immune epitopes of EBV can be mutated, making it difficult for specific CTLs to recognize the virus; (iv) interference with the cytokines: BNRF1 counteracts the proliferative effect of colony-stimulating factor-1 on monocytes, thereby blocking the interferon–mediated intrinsic immune response against the virus [30,31]; (v) EBV-encoded RNA (EBER) suppresses the activity of T cells and maintains the stability of EBV mRNA to reduce the antigen presentation of MHC to evade immunity; (vi) encoding microRNAs: EBV can encode more than 40 kinds of microRNAs, and microRNAs are secreted extracellularly in the form of exosomes, transmitting between EBV-infected B cells and uninfected B cells to protect miRNAs from hydrolysis by RNase [32]. EBV can also downregulate the latent membrane protein LMP2A to avoid CTL recognition, allowing B cells infected with EBV to escape CTL killing [33].

**EBV-related diseases**

**Hematologic disorders**

**Infectious mononucleosis**

IM is a disease caused by EBV infection, which occurs most commonly among adolescents and young adults [34]. IM is an acute self-limited disease, and most patients have a good prognosis [35]. However, a small number of patients will progress to hemophagocytic syndrome and other complications. EBV infection is one of the causes of IM. It has been proven that LMP1 promotes the progression of IM [36] and affects the body's immunity. In clinical work, we can evaluate the disease and carry out an individualized treatment plan according to the level of LMP1. Infusion of specific CTLs can inhibit the proliferation of infected cells in patients with acute IM [37].

**Hodgkin lymphoma**

HL is one of the major types of lymphoma. Latent EBV infection can be detected in approximately one of three of patients diagnosed with HL. Studies have shown that in Europe and the United States, more than 30% of HL cases are associated with EBV [33,38]. As early as 1987, Weiss et al. [39] experimentally identified EBV-DNA in HL.

**Figure 1.** (1) EBV infects B cells and releases viral DNA into B cells. Then, the virus replicates in the host cell. When EBV infects B cells again, memory T cells will reactivate EBV-specific cytotoxic T cells to kill the cells that infected with EBV specifically. (2) After EBV replicates in B cells, it will continue to infect epithelial cells or B cells. In most cases, EBV exists in these cells in a latent state. EBV is transmitted primarily via saliva. (2) In the process of infecting cells, EBV glycoproteins bind to host cell receptors. Integrins, NRP1 and MHC-IIA can interact with BMRF2, gH, gL and gB. EphA2 binds to gH, gL and gB. The viral membrane fuses with the host membrane. Then, the viral capsid passes through the cytoplasm and is transported to the host cell's nucleus. Finally, the virus is released into the nucleus by penetrating the nuclear pore for replication and proliferation.
The rate of EBV positivity in HL is correlated with sex and age, with male patients having a greater rate of positivity than female patients, and children and older adults having a greater rate than young adults [40]. However, the pathogenesis of the disease is not fully understood. EBV encodes LMPs, EBERs and EBNA1. LMP1 acts on immunosuppressive factors and activates transcription factors [41], and it can also activate JAK/STAT5 phosphorylation to upregulate the expression of programmed death-ligand 1 to change the microenvironment of HL [42]. LMP1 can bind to CD40 to activate NF-κB. The incorrect activation of NF-κB may cause tumorigenesis [43]. This activity upregulates many anti-apoptotic proteins and enhances the expression of cell surface markers associated with invasion [44]. The coordinated expression of NF-κB regulatory proteins can protect EBV-infected lymphoma cells from apoptosis [45]. The expression of anti-apoptotic proteins cIAP-1, cIAP-2, and cFLIPL of NF-κB protects cells from the stimulation of activating death receptors and mitochondria-dependent death pathways [46].

**Diffuse large B-cell lymphoma**

Approximately 10% of DLBCL is associated with EBV infection, with a slightly greater proportion of DLBCL in Asia and Latin America being EBV-positive [47]. Patients with EBV-positive DLBCL have a worse prognosis than EBV-negative patients [48]. Wu et al. [49] showed that EBV-encoded LMP1 can regulate the expression of erythropoietin and hematopoietic receptor A4 (EphA4) through the extracellular signal-regulated kinase-SPI (ERK-Sp) pathway and confirmed that EphA4 expression blocks lymphocyte proliferation. Furthermore, the level of EphA4 expression was decreased in patients with DLBCL and EBV infection, which significantly correlated with their poor prognosis [49].

**Burkitt lymphoma**

Burkitt lymphoma is a highly invasive non-Hodgkin lymphoma (NHL) that is classified into three clinical variants: endemic, sporadic and immunodeficiency-related [50]. In Africa, EBV is closely related to the development and progression of BL, mainly endemic BL [32]. Almost all endemic BL is related to EBV infection, whereas only 5–15% of sporadic BL is associated with EBV infection, and 30–40% of immunodeficiency-associated BL is suggestive of EBV positivity [51,52]. The main causative agent of EBV-associated Burkitt lymphoma has not been determined, but EBNA1, EBER and LMP1 have all been hypothesized to play a role, as they are highly expressed in most cases of EBV-positive Burkitt lymphoma [48]. There is a repetitive glycine–alanine (Gly-Ala) sequence in the EBNA1 structure, which can block binding to TAP transporters and affect antigen presentation [53]. Kennedy et al. [54] found that EBNA1 can maintain the continuous growth of lymphoma cells after the formation of Burkitt lymphoma cells.

**NK/T-cell lymphoma**

NK/T-cell lymphoma (NKTL) is an EBV-related malignant tumor, most of which originates from natural killer (NK) cells, and only a few originate from T cells [55]. It can be divided into nasal, non-nasal and diffuse. In patients with NKTL, the rate of EB virus positivity is more than 90%. EBV-DNA detection can evaluate the prognosis of the disease [56]. The pathogenesis of NKTL is also unclear. Ramakrishnan et al. [57] found that LMP1 expression was increased and tumor cells proliferated vigorously when miRNA in the coding region of EBV was upregulated. LMP1 in combination with tumor necrosis factor receptor activates NF-κB and the mitogen-activated protein kinase pathway through the ERK, JNK, p38 and JAK/STAT pathways, resulting in tumor cell proliferation and invasion. In addition, EBV-infected cells express limited antigens so that they can escape CTL supervision. All of these conditions may lead to NKTL [58].

**Other EBV-associated diseases**

**Nasopharyngeal carcinoma**

NPC is an epithelial carcinoma originating from the mucosal lining of the nasopharynx [59]. The World Health Organization pathological classification is mainly divided into keratinous squamous cell carcinoma (type I), differentiated nonkeratinizing carcinoma (type II) and undifferentiated nonkeratinizing carcinoma (type III). The main etiological factors of NPC include genetic factors, environmental factors and EBV infection [60]. In NPC cells, EBV is in an episomal form and is not integrated into the host genome. In almost all nonkeratinized NPC, EBV adopts the form of latency II in NPC cells. Only limited viral genes are expressed, including EBERs, EBNA1, LMPs and BARF1 [61]. LMP1 has been identified in approximately two-thirds of NPC cases [62]. LMP1 expression inhibits the AMPK/LKB1 signaling pathway to promote cell growth and survival [63]. In epithelial cells, LMP1 induces specific forms of NF-κB. In NPC, NF-κB p50/p50 homodimers may be important factors and contribute to tumorigenesis [64].

**Posttransplant lymphoproliferative disorder**

allo-HSCT is an important treatment for a variety of malignant and nonmalignant diseases and can effectively prolong the survival time of patients [65]. However, due to the use of immune-suppressants, the function of the immune system is reduced, and latent EBV may be easily reactivated. PTLD is a heterogeneous disease caused by decreased immune response and loss of EBV surveillance in patients post-transplant [65]. Studies have shown that in HSCT, the occurrence of PTLD is almost always related to EBV [66]. Although the incidence rate is low, the case fatality rate is 84.6% [67]. Patients with solid-organ transplantation or HSCT create special conditions for immune dysfunction due to pretreatment chemotherapy or the use of immunosuppressive agents, creating a suitable environment for progression to PTLD [68].

**Gastric cancer**

Gastric cancer (GC) is the fifth most common cancer in the world and the fourth-leading cause of cancer death worldwide [69]. GC can be classified into EBV-positive tumors, microsatellite unstable tumors, genomically stable tumors and chromosomal instable tumors [70]. EBV was associated with 7.5% of GC [71]. Approximately 50% of EBV-positive GC expressed LMP2A, which can be recognized and targeted by cytotoxic T lymphocytes [72].

**Multiple sclerosis**

MS does not develop in the absence of exposure to EBV. There is a strong correlation between the presence of anti-EBV antibodies in the blood and the onset of the disease [73,74], and EBV may contribute to the progression and relapse of MS; some investigators even support a causal relationship between them [75].

**EBV-CTLs**

CTLs are T-cell populations that kill target cells specifically [76]. They secrete a variety of cytokines, participate in host immune regulation and target killing of virus-infected cells or tumor cells. CTLs are a vital line of defense for the body against viruses and tumors. There are two mechanisms by which CTLs kill target cells: lytic killing and apoptosis [77]. Lytic killing occurs when CTLs act on the cell membranes of target cells by secreting substances such as perforin, resulting in cell lysis. In the process of apoptosis CTLs use FasL on their surface to bind to Fas on the surface of target cells or transfer granzyme B cells to stimulate cell apoptosis (Figure 2) [77].
Figure 2. Killing mechanisms of CTL. The recognition of peptide-major histocompatibility complexes (pMHCs) by the T-cell receptor (TCR) is the initial step to mediate T-cell immunity. CD28 binds to B7 on antigen-presenting cells and plays a vital role in the activation of T cells. CD28 is a costimulatory molecule expressed on the surface of T lymphocytes and plays an important role in the activation of T cells. It binds to B7 molecules on antigen-presenting cells and promotes cytokine production. Lysis and killing: after CTLs contact a target cell, they activate various signals and then act on the cell membrane of the target cell mainly by secreting perforin and other substances, resulting in cell lysis. CTL-mediated apoptosis: CTLs stimulate apoptosis by binding FasL to Fas on the surface of target cells or by transferring granzyme B around cells.

**Comparison of advantages and limitations of various methods.**

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<th>Method</th>
<th>Advantages</th>
<th>Limitations</th>
<th>References</th>
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<tr>
<td>Preparation of CTLs by B-LCLs</td>
<td>Use the patient’s PBMCs to reduce the incidence of GVHD; short preparation time; CTLs have more vital specificity; high efficiency and no cumbersome cell cloning; maintain immune memory for a long time.</td>
<td>Time-consuming; complex steps. Higher cost; only applicable to seropositive donors; restricted to certain HLA types.</td>
<td>[78]</td>
</tr>
<tr>
<td>Preparation of CTLs by DCs</td>
<td>The preparation time for CTLs was significantly shortened; not restricted to certain HLA types.</td>
<td>Not suitable for EBV-seronegative donors or for seropositive donors with extremely low frequencies of CD3 IFN-γ cells and IFN-γ low-expressing T cells.</td>
<td>[82,83]</td>
</tr>
<tr>
<td>IFN-γ capture technology</td>
<td>Cryopreserved third-party EBV specific T cells are immediately available and can be selected based on their partial HLA restriction and HLA matching levels.</td>
<td>Injection of a lymphodepleting environment is not sufficient by itself to guarantee CTL expansion and long-term persistence.</td>
<td>[84,85]</td>
</tr>
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</table>
EBV-CTLs for the treatment of other EBV-related diseases

As early as 1995, Rooney et al. [94] published an article reporting that they used B-LCLs of the patient’s own origin to stimulate CTLs and treat EBV-associated lymphoproliferative disorders. The patients had significantly reduced complications after treatment and the method was considered safe and effective. In 1999, Khanna et al. [95] used EBV-CTLs to treat patients with solid-organ transplant. They found that patients with solid-organ transplants also had the potential to activate effective, CTLs and that activated CTLs were strongly EBV-specific and responsive. EBV-CTLs also have great prospects in the treatment of NPC. Comoli et al. [96] prepared EBV-CTLs from donor PBMCs matched with the patient’s HLA to treat recurrent NPC. They found that patients tolerated the treatment well, and their condition remained stable for 3 months. Because there was only one patient, the same group conducted a clinical trial again. They selected 10 patients with EBV-associated stage IV NPC after conventional radiotherapy and chemotherapy and infused LMP2 EBV-CTLs into these 10 patients. None of these patients experienced any acute adverse reactions during the administration period. The disease was controlled in six of 10 patients. Two patients had PR, and four had stable disease. The authors concluded that EBV-CTLs were beneficial in the treatment of NPC [97]. In 2017, Huang et al. [98] screened 21 of 28 patients with recurrent metastatic NPC enrolled for a clinical trial of EBV-CTLs. In this trial, only one patient had a CR, and the remaining patients experienced disease progression (NCT00431210 and NCT00834093). The authors concluded that further research is needed on options for treating NPC with EBV-CTLs, but they did not deny the potential positive aspects of EBV-CTLs. Third-party EBV-CTLs emerged as a promising potential therapy for patients with EBV-associated lymphoma refractory to rituximab after transplantation. In the treatment of NPC, it is feasible and safe to combine EBV-CTLs in the first-line treatment.

In patients with MS treated with EBV-CTLs, no adverse effects were noted, and their discomfort was relieved. Fatigue is the most common symptom of MS. After treatment with EBV-CTLs, patients perceived less fatigue than before [99] (ACTRN12615000422527). The safety and efficacy of EBV-CTLs in the treatment of MS provide further evidence that the onset of MS is associated with EBV and lay the foundation for the development of EBV-CTLs in the clinic. The treatment information for several diseases is shown in Table 2 [99–102].

Limitations of CTLs

Even though CTLs are more effective, their use is still not widely practiced in the clinic for several reasons. First, the cost of preparing CTLs is too high [103]. Even if hospitals or research centers can produce qualified CTLs, patients may not be able to pay for them. The high cost of generation is an insurmountable difficulty for both patients and research centers. In previous experiments, some patients who received EBV-CTL treatment showed an increase in EBV-DNA after treatment [104]. Reinforcement of EBV-CTL treatment is also ineffective, and patients eventually progress to PTLD or even death. Patients need regular infusions of EBV-CTLs to maintain their health status. Long-term use of EBV-CTLs may require greater doses or shorter infusion intervals to achieve therapeutic benefits, which indirectly increases the cost of treatment for patients. Although Heslop et al. [103] detected the presence of CTLs in patients who survived for more than 10 years in a long-term follow-up, we cannot definitively conclude that CTLs can exist and proliferate stably in vivo. In addition, immunosuppressants are typically used when patients undergo pretreatment chemotherapy before transplantation and post-transplantation for graft versus-host disease (GVHD) prophylaxis. The use of immunosuppressants will shorten the life of CTLs to a certain extent. In patients with severe NPC, EBV-CTL treatment is almost ineffective [98]. The effective time of CTLs used in vivo is influenced by many factors, so this approach does not exert the greatest antitumor advantage. CTL therapy in patients with EBV+ lymphoma

Table 2

<table>
<thead>
<tr>
<th>Diseases</th>
<th>Peripheral blood source</th>
<th>Treatment effectiveness</th>
<th>Safety</th>
<th>References</th>
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<tr>
<td>HL</td>
<td>Patients themselves</td>
<td>Three of 12 patients with severe disease were not relieved. Of the 10 patients with detectable EBV-DNA, nine had DNA decline after CTL infusion.</td>
<td>Temporary flu-like symptoms (14%).</td>
<td>(NCT0058773)</td>
</tr>
<tr>
<td>NKTCL</td>
<td>Two cases from HLA-matched donors; one case of self-derived CTLs.</td>
<td>Two patients (one who received EBV-CTLs from a donor and one who received self-derived EBV-CTLs) remained stable for more than 3 years and received T-cell therapy twice.</td>
<td>There was no immediate severe inflammatory response and no severe toxicity during treatment.</td>
<td>(100)</td>
</tr>
<tr>
<td>PTLD</td>
<td>HLA-matched donor.</td>
<td>1. In PTLD of SOT, seven of 10 of the children patients achieved CR, and the 2- and 5-year survival rates were 89% and 86%, respectively.</td>
<td>1. No toxic reactions occurred</td>
<td>(101)</td>
</tr>
<tr>
<td>CAEBV</td>
<td>Patients themselves</td>
<td>2. Patients with HSCT received preventive therapy for up to 2 years.</td>
<td>There were no immediate and delayed adverse reactions</td>
<td>(102)</td>
</tr>
</tbody>
</table>

B-LCL, B lymphoblast cell line; CAEBV, chronic active EBV infection; CR, complete response; CTL, cytotoxic T lymphocyte; EBV, Epstein-Barr virus; HL, Hodgkin lymphoma; HLA, human leukocyte antigen; HSCT, hematopoietic stem cell transplantation; NKTCL, NK/T-cell lymphoma; PTLD, post-transplant lymphoproliferative disorder; SOT, solid-organ transplant.
Therapeutic EBV Vaccines

The treatment of cancer mostly uses radiotherapy or chemotherapy, but these two treatment modalities have been associated with many side effects. It is of universally interest to develop novel immune-based, tumor-specific therapeutic approaches with limited side effects and low off-target toxicity [109]. At present, therapeutic EBV vaccines are mainly targeted at NPC. Early clinical trials were conducted with EBV vaccine based on DCs. The vaccine targets are EBNA1, LMP2 and/or LMP1 [110,111]. In patients with advanced metastatic NPC, autologous DCs transduced with adenovirus vector encode truncated LMP1 (ΔLMP1) and full-length LMP2 (Ad-ΔLMP1- LMP2) [112]. There were 16 subjects in this clinical trial. All patients were tolerant to the treatment and had no obvious side effects. LMP2-specific T-cell responses has improved in nine of 16 patients, which was associated with a modest reduction in serum EBV DNA levels [112].

An additional approach is vaccination using a modified Ankara vaccinia (MVA) recombinant vector expressing tumor associated viral antigens [113]. The vaccine virus, MVA-EL, encodes a functionally inactive fusion protein containing the C-terminal half of EBNA1 and full-length LMP2A [114]. In this group of clinical experiments, adverse events in 18 patients were mainly limited to mild injection sites and transient systemic reactions. The results of the first vaccine trial in patients with NPC with disease remission after conventional therapy showed that the MVA-EL vaccine was both safe and immunogenic [113]. A phase 1 clinical trial of MVA-EL vaccine in the United Kingdom showed that patients with NPC have good overall tolerance to vaccination. Immunity increased after vaccination in eight of 14 patients [115].

EBV Specific T-Cell Receptor–Engineered T-Cell Therapy

CAR T cells are designed to have chimeric antigen receptor genes targeting specific tumor epitopes, which are then proliferated in vitro and transfused back into patients to kill particular tumor cells. CAR-T cells are fundamental to the killing of cancer cells by engineering immune cells in the body to allow the immune system to turn on the body's self-purification mechanisms. The ability of CAR-T cells to completely clear cancer cells is beneficial to the stabilization of the disease condition of cancer patients. Although cytokine release syndrome may occur in patients after CAR-T infusion, CAR-T-cell immunotherapy has played a pivotal role in hematological diseases [116-119].

Targets of CAR-T

The EBV glycoprotein gp350 is the most abundant glycoprotein in viruses and virus-infected cells and is the major target of naturally occurring neutralizing antibodies. Gp350 confers viral tropism to B cells through interaction with the B lineage marker CD21 [120,121]. If EBV-negative recipients can be immunized before transplantation, then the risk of PTLD may be reduced. There were researchers used 72A1, a monoclonal antibody (mAb) against gp350, to conduct experiments in mice. They also injected purified 72A1 mAb into healthy adults and four EBV-negative children after liver transplantation. The results of the in vivo experiments in mice showed that no mice in the experimental group progressed to malignant tumors, compared with eight of 12 mice in the control group that progressed to EBV-positive tumors. In a clinical trial, only one child had a hypersensitivity reaction, whereas the remaining three children and one healthy adult had no adverse reactions [122]. Due to the paucity of data, the prophylactic treatment with mAbs in the clinical setting needs to be further investigated. B-chronic lymphocytic leukemia cells loaded with gp350 + exosomes can stimulate the generation of specific cells in vitro. Such specific cells can kill tumor cells [123]. Therefore, gp350 is promising as an ideal target for the treatment of EBV-related diseases. An experimental group has designed CAR-T targeting gp350 and conducted experiments [124]. Their experiments found that the weights remained normal in mice treated with CD8+ gp350 CAR-T cells and that the transmission of the virus was decreased in nine of 12 mice. Mice had a weak inflammatory response and no tumor development. However, 25% of the mice had an exacerbation of EBV infection. Despite the emergence of adverse events, CD8+ gp350 CAR-T-cell therapy still has clinical development potential [124].

AMMO1 is an anti-gHgL antibody that neutralizes epithelial and B-cell infections in vivo and in vitro. One study has shown that it is the only anti-gHgL mAb that can completely neutralize B-cell infection, and it shows the same potency as the anti-gp350 mAb 72A [125]. Singh et al. [125]. injected purified recombinant AMMO1 into humanized mice. In the experimental group, the spleen weight of 11 of 13 mice was equal to that of uninfected mice. In eight of 11 mice, trace amounts of the virus were detected by spleen DNA testing. Their experiments also compared AMMO1 with 7A1, and the results were slightly different from those of Snijder et al. [126]. In Singh's group, the neutralization ability in vitro of the AMMO1 group was stronger than that of the 7A1 group. AMMO1 can block the transmission of lymphatic cryptovirus in vivo by limiting the infection of human B cells in humanized mice and preventing oral transmission in nonhuman primate models [127]. These findings strongly support the possibility that AMMO1 may become an effective target for EBV-CART in the treatment of EBV-related diseases. [104]
CAR-transduced CTLs

The expression of CARs in CTLs redirects activated T cells (through their natural TCR and costimulatory pathways) to their new targets, creating tumor-specific CAR gene modification of EBV-CTLs. CAR-transduced CTLs can target EBV-infected B cells and tumor cells. Theoretically, treatment with CAR-transduced CTLs followed by transplantation could reduce the risk of PTLD in patients with refractory/relapsed lymphoma and may also improve their prognosis.

HL cells lack expression of immunodominant EBV antigens [126] and weaken antigens lead to tumor escape; thus, CTL therapy may fail. Almost all Hodgkin Reed-Sternberg cells overexpress CD30, a member of the TNF family. Savoldo et al. [128] modified EBV-CTLs with CD30-specific CAR (CD30.CAR EBVST). In vitro experiments showed that CD30.CAR EBVST broke through MHC restriction. EBV CTLs can still kill EBV-expressing targets through their native receptors. In the xenograft model, CD30.CAR EBVST produced antitumor effects on EBV-negative tumors. CD30.CAR EBVST will not damage the whole immune system. In an update from the 2022 American Society of Hematology meeting, this team has evaluated this approach in a phase 1/2 trial (NCT04288726) in patients with CD30-positive lymphoma. In this clinical trial, 14 patients with relapsed or refractory HL were enrolled. Escalating doses of $4 \times 10^7$ (Dose Level 1), $1 \times 10^8$ (Dose Level 2) or $4 \times 10^8$ (Dose Level 3) CD30.CAR EBVST cells were infused after lymphodepletion with cyclophosphamide and fludarabine. Four patients had PR, and five in 10 patients in DL2 and DL3 groups had CR, with an overall objective response rate of 69.2%. They have shown that CD30.EBVSTs can be a safe and effective treatment for CD30+ lymphomas, and may avoid GvHD and immediate rejection even after multiple infusions.

In treating acute myeloid leukemia, the combination of CAR and CTL is also promising. Some researchers introduced CD33.CAR into EBV-CTLs and found that CTLs could stably express CD33.CAR without affecting the function of the original EBV-CTLs. In vitro experiments showed that the CTLs had myeloblastic activity. In vivo experiments in mice showed that CD33.CAR EBVSTs reduced the progression of acute myeloid leukemia but for a shorter duration in vivo [129].

Human induced pluripotent stem cells (iPSCs) can constantly renew themselves and differentiate into different types of cells [130]; these cells have become a promising tool for the treatment of various refractory diseases [131]. Compared with the original CTLs, iPSC-derived CTLs have greater proliferation ability and longer telomeres [106]. Through iPSC technology, antigen-specific CTLs can be regenerated functionally to produce regenerated CTLs (rejTs) [132]. In most cases, EBV-associated lymphoma cells express LMP1 and LMP2, which are good targets for cell surface CARs and TCRs associated with HLA class antigens. Japanese researchers have produced rejTs targeting LMP1 and LMP2 through iPSCs. They found that two specific rejTs showed strong cytotoxicity against ENKL and EBV tumor cells in vitro. In vivo experiments showed that the rejTs group exhibited stronger inhibition of ENKL than the original CTL group, and the mice survived longer than 7 months. After three injections of rejTs, the ENKL tumors were completely cleared. Through the immunohistochemical analysis of spleens sections, the spleen of the rejTs group were found to be full of CD3 T cells. Through a 51Cr release assay, the tumor cells were determined not to be resistant to rejTs treatment [133]. Harada et al. [134] combined CAR with rejTs to develop double-antigen receptor (DR) rejTs (DRejTs) to overcome the shortcomings of traditional CTL and CAR-T therapy in preventing antigen escape, in vivo persistence and other effects. Their experimental data show that the inhibition of ENKL tumors by DRejTs in vivo and in vitro is stronger than that of traditional CARTs. DRejTs significantly prolonged the survival time of treated mice. They inoculated ENKL cells into mice that survived for 110 days and found that DRejTs existed for a long time in vivo and successfully eliminated the reinoculated ENKL cells. DRejTs targeting CD19 and LMP2 antigens that were generated by Harada et al. [134] also strongly blocked the proliferation of LCLs. If we produce different HLA-restricted CTL lines from healthy donors, DRejTs treatment will benefit a large number of patients and solve a major clinical problem. If CAR-T cells and CTLs could be combined to cure the disease so strongly, rapidly and precisely and be able to reduce the occurrence of side effects, it would be a significant advance for the benefit of all humankind.

Conclusions

EBV infects more than 95% of the population and causes IM among 70% of adolescents and young people in developed countries, accounting for 1.5% of all cancers in the world and 1.8% of all cancer deaths. Various research groups are actively working on the early diagnosis, treatment and prevention of EBV infection. EBV envelope proteins, such as gB, gp350, play an important role in EBV entry and infection of its target cells. EBV-CTLs are a potential treatment for EBV infections that have failed to respond to conventional treatment. Because the generation of EBV-CTLs is complex and takes a long time, it is mainly used in observational research with a small sample size in clinics. However, the emergence of third-party EBV-CTLs libraries means that they have tremendous potential to enter the clinic and carry out large-scale treatment. Recently, an Australian research institute has been investigating the combination of third-party CTL libraries with traditional antiviral approaches for the treatment of diseases caused by EBV. Phase 1 clinical trial results showed that conventional antiviral treatment combined with early administration of third-party CTLs was safe, and there was no acute or chronic GvHD. Therapeutic EBV vaccines targeting the latent proteins EBNA1, LMP2 and/or LMP1 are positive treatments. Although there are still limitations in current EBV therapeutic vaccines, different vaccine platforms that target latent and lytic envelope proteins at same time can be explored to improve efficacy. EBV-specific CAR-T cell therapy for LMP1, LMP2 and gp350 also needs to be further optimized and developed in clinical practice.

Although many mechanisms of EBV infection remain unresolved, it is believed that future treatments for EBV-related diseases will be continuously updated and more robust, and the safety and efficacy of existing technologies are expected to increase significantly.

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Author Contributions

Conception and design of the study: YZ, HRL. The major contributor to writing the manuscript: YZ. Acquisition of data: 2021.11-2022.10. Analysis and interpretation of data: 2021.11-2022.11. Drafting or revising the manuscript: YZ, HRL, XJ and GRT. All authors have approved the final article.

Declaration of Competing Interest

The authors have no commercial, proprietary or financial interest in the products or companies described in this article.


