Epstein-Barr virus (EBV) reactivation and therapeutic inhibitors

Jonathan R Kerr

ABSTRACT

Epstein-Barr virus (EBV) is a ubiquitous human virus which infects almost all humans during their lifetime and following the acute phase, persists for the remainder of the life of the individual. EBV infects B lymphocytes leading to their immortalisation, with persistence of the EBV genome as an episome. In the latent phase, EBV is prevented from reactivating through efficient cytotoxic cellular immunity. EBV reactivates (lytic phase) under conditions of psychological stress with consequent weakening of cellular immunity, and EBV reactivation has been shown to occur in a subset of individuals with each of a variety of cancers, autoimmune diseases, the autoimmune-like disease, chronic fatigue syndrome/myalgic encephalitis and under other circumstances such as being an inpatient in an intensive care unit. Chronic EBV reactivation is an important mechanism in the pathogenesis of many such diseases, yet is rarely tested for in immunocompetent individuals. This review summarises the pathogenesis of EBV infection, EBV reactivation and its role in disease, and methods which may be used to detect it. Known inhibitors of EBV reactivation and replication are discussed, including drugs licensed for treatment of other herpesviruses, licensed or experimental drugs for various other indications, compounds at an early stage of drug development and nutritional supplements such as vitamins and dietary supplements.

INTRODUCTION

Epstein-Barr virus (EBV) is a ubiquitous human virus which infects almost all humans during their lifetime and persists for the remainder of the individual. EBV reactivates under psychological stress, and EBV reactivation has been shown to occur in a subset of individuals with each of a variety of autoimmune diseases and cancers. It is recognised that chronic EBV reactivation is an important mechanism in the pathogenesis of these diseases. Yet EBV reactivation is rarely suspected in clinical practice, is rarely tested for in immunocompetent individuals and, even if identified, there are no licensed treatments. In this review, the importance of EBV reactivation will be considered in the pathogenesis of disease in general, along with diagnostic approaches and therapeutic inhibitors, including drugs, vitamins and supplements.

EBV infection

EBV is a hugely successful virus which maintains a global infection rate in humans of 95% and persists lifelong in individuals following the acute phase of infection. In immunocompetent individuals, this persistence is not associated with clinical symptoms. Primary EBV infection is usually asymptomatic and for many occurs during childhood, but when it occurs in adolescence or adulthood, 30%–50% cases manifest clinically as infectious mononucleosis (IM). Primary and secondary immunodeficiency facilitates virus reactivation, unchecked proliferation of EBV-infected B lymphocytes and eventual development of EBV+ B lymphoproliferative disease. EBV infection of T cells/natural killer (NK) cells may result in haemophagocytic lymphohistiocytosis, chronic active EBV infection and T-cell/NK-cell lymphomas, which tend to be aggressive in presentation. EBV also causes Burkitt lymphoma (BL), nasopharyngeal carcinoma (NPC), gastric adenocarcinoma, AIDS-associated lymphoblastic and primary central nervous system lymphoma, post-transplant lymphoproliferative disease (PTLD), nasal T-cell/NK lymphoma, Hodgkin’s disease, lymphoepithelioma-like carcinoma and leiomyosarcoma. Altered immune responses to EBV have been documented in a wide variety of autoimmune diseases, including multiple sclerosis (MS), Sjögren’s syndrome (SS), systemic lupus erythematosus (SLE), rheumatoid arthritis (RA), inflammatory bowel disease (IBD) and type 1 diabetes mellitus (T1DM). EBV infection has been associated with a higher risk of developing autoimmune disease, particularly MS, dermatomyositis, SLE, RA and SS.

EBV is a gamma-herpesvirus, containing double-stranded linear DNA of 170–175 kb, which is transmitted mainly by salivary transfer of EBV-infected B cells, but also by aerosol. Although it is generally accepted that early subclinical infection is predominant in developing countries, 80% Japanese children have acquired the virus by the age of 3. In the oropharynx, the virus infects B cells via the C3d complement receptor, CD21. It has been shown that the epithelial lining of the oropharynx is discontinuous allowing the virus direct access to the underlying B cells of the tonsils. EBV infection of B lymphocytes in vitro leads to the production of immortalised lymphoblastoid cell lines exhibiting restricted cellular and EBV gene expression. After the initial replicative (lytic) phase of infection, the EBV genome circularises to be maintained as a multicopy plasmid in the B cell nucleus. In almost all EBV-infected B cells, the virus infection exists in a latent state, with the capacity for cellular immortalisation. In vivo, latent EBV+ B cells include immunoblastic B cells, memory B cells and resting non-immunogenic B cells. Immunoblastic B cells are highly immunogenic and are rapidly removed during IM.
Resting non-immunogenic B cells are the latent virus reservoir in the circulation of healthy carriers.1

IM is the primary virus infection which occurs in EBV seronegative persons; 80% or more cases of acute IM are due to primary EBV infection. IM symptoms include fever, tender lymphadenopathy, sore throat, hepatosplenomegaly and skin rash. Symptoms characteristic of EBV-infected IM patients, as opposed to IM due to infection with cytomegalovirus (CMV) or varicella-zoster virus (VZV), are puffy eyelids and tonsillar exudates.1 Young children more frequently have skin rash and abdominal pain. By the end of the incubation period (2 to 7 weeks post-transmission), EBV has spread to infect approximately 20% B cells in infected adolescents and young adults with acute IM.2 The proliferation of EBV-infected B lymphocytes is rapidly inhibited during the first 2 weeks by a strong cellular immune response. This was previously believed to be composed of only NK cells, interferon-γ (IFN-γ)-activated CD8+ T cells and antibody-dependent cellular cytotoxicity.14 Activated CD8+ T cells (morphologically seen as atypical lymphocytes) may reach 60% peripheral blood mononuclear cells (PBMCs) during the symptomatic phase of acute IM.15 T lymphocytes specific for EBV lytic phase epitopes have been shown to account for up to 44% of total CD8+ T lymphocytes, in comparison with 1%–2% accounted for by CD8+ T lymphocytes specific for the immunodominant EBV proteins, Epstein-Barr nuclear antigens EBNA3, EBNA4 and EBNA6.16 17

More recently, the importance of polyfunctional T cells (PFCs) in control of EBV has been recognised. EBV-specific PFCs in long-term carriers produce more cytokines per cell than the single functional T cells and may be functionally superior.18 19 It has been shown that CD4+ and CD8+ PFC responses occur against immunodominant latent and lytic EBV epitopes during primary EBV infection in children.20 PFCs have multiple functions, such as simultaneous production of multiple cytokines, for example, interleukin 2, IFN-γ and tumour necrosis factor α, and degranulation of cytotoxic proteins. PFC appear to be associated with more effective control of chronic microbial infections including HIV, hepatitis C virus (HCV) and CMV.21 22 Frequencies of occurrence of PFC were higher in HIV non-progressors than in progressors.23 It has recently been shown that polyfunctional and IFN-γ monofunctional CD4+ T cells are molecularly distinct and the polyfunctional gene signatures in response to infection with Plasmodium falciparum and influenza virus are highly conserved.24 Therefore, PFC appear to contribute to more robust T-cell immunity in control of virus infections. But how they arise and evolve during primary EBV infection and their role in long-term control of EBV remains unknown.

During the symptomatic phase, 103–4 copies of EBV DNA can be detected in PBMC or serum.28 29 Occurrence and progression of EBV-specific antibodies are used for the diagnosis of acute EBV infection. The cellular immune response reduces the number of circulating EBV-infected B cells to 1 in 106 B cells within 4–6 weeks.1

**PATHOGENESIS OF EBV INFECTION**

**Lytic phase of infection**

During lytic infection (EBV replication), on the other hand, the EBV genome is amplified up to 1000-fold by the viral replication machinery. The lytic phase is also associated with the expression of nearly 100 EBV genes. The lytic programme arrests cell cycle progression and favours the S-phase which provides the cellular environment necessary for viral replication.30 The expression of the immediate early proteins, Zta and Rta (encoded by BZLF1 and BRLF1, respectively), initiate the EBV lytic phase of infection.31 Zta and Rta activate the expression of one another and trigger the expression of a panel of early lytic proteins (BMRF1, BALF1, BHRF1 and others). Thus, viral DNA replication and later, expression of late lytic proteins are initiated by the immediate early and early EBV lytic proteins.32 In the complete lytic cycle, viral DNA is replicated as large, complete molecules which are later cleaved and packaged into viral progeny which are released to infect neighbouring cells.33

EBV reactivation has been shown to occur following impairment of the cellular immune response caused by psychological stress of various types, including student examination stress,34 35 marital stress,36 attachment anxiety or fear of abandonment and rejection,41 and loneliness.42 EBV reactivation has also been shown to occur with greater than 5 to 7 days spent as a patient in intensive care,43 44 which is well recognised to be associated with post-transplant BL.30–32

**EBV protein expression facilitates this process, especially latent membrane proteins (LMP1, LMP2A, LMP2B) and EBV nuclear antigens (EBNA1, EBNA2, EBNA3A, EBNA3B, EBNA3C). Three different latency patterns are recognised depending on the pattern of protein expression, each of which is associated with a different stage of B-cell infection and with particular lymphoproliferative disorders. Latency III is the most elaborate viral expression pattern (EBER1, EBER2, EBNA1–6, LMP1, LMP2A, LMP2B) and is associated with EBV+ post-transplant diffuse large B-cell lymphoma (PT-DLBCL). Latency II is more restricted in its protein expression (EBER1, EBER2, EBNA1, LMP1, LMP2A) and is associated with PT-DLBCL and Hodgkin lymphoma.**

**EBV reactivation has been shown to be an important factor in the pathogenesis of NPC**33 and PTLD.32 It has been shown that an NPC-associated BZLF1 variant is associated with the enhancement of lytic EBV infection.34 PTLD has also been shown to be associated with detectable circulating EBV genome and ZEBRA, the gene product of BZLF1.54

Indirect evidence for EBV reactivation is provided by the upregulation of the human EBV-induced 2 (EBI2) gene, which is the most upregulated human gene in EBV-infected BL cells.55 EBI2 upregulation has been demonstrated in melanoma metastases, lymphoblastic leukaemia, glioblastoma, bone cancer metastasis, SLE, chronic rhinosinusitis with nasal polyps, T1DM and CFS/ME.55 EBI2 is a human G-protein coupled receptor (GPCR) which is activated by oxysterols and pertussis toxin-sensitive heterotrimeric G proteins, resulting in decreased cyclic
expression.56 Proteins, circulating EBV genome, and EBI2 gene and protein T lymphocytes (ELISpot assay) against EBV latent and lytic viral sclerosis, IBD and osteoporosis.56

EBV reactivation may be identified in individuals by detection of a IgA antibody to EBV early antigen (EA), neutralising IgG to EBV DNA polymerase and EBV dUTPase.49 51 IFN-γ release from T lymphocytes (ELISpot assay) against EBV latent and lytic viral proteins, circulating EBV genome, and EBI2 gene and protein expression.56

Oral hairy leucoplaquia (OHL) as a model of EBV reactivation

Although circulating resting memory B lymphocytes are believed to be the reservoir of latent EBV,62 63 EBV can replicate in human oral epithelial cells and EBV may be detected in oral tissue as a latent infection.57 68 OHL is a benign oral epithelial disease presenting as white patches which is associated with active EBV infection of oral epithelial cells which is frequently seen in HIV infection, IM and with psychological stress.69 Treatment of this condition with drugs that inhibit EBV replication leads to resolution without eradication of latent infection.67 Therefore, OHL has been used as a model for EBV reactivation, factors involved and potential therapeutics.

Therapeutic oncolytic therapy for EBV-associated neoplasia

While EBV reactivation is an important causative mechanism of disease for many patients, it also represents a potentially effective therapeutic intervention for others. Deliberate reactivation of the EBV lytic cycle is a therapeutic strategy that exploits the presence of EBV genome in cancer cells. Induction of EBV lytic cycle can directly induce apoptotic cell death in EBV-infected cell lines.70–73 And it has been demonstrated that EBV reactivation using tetradecanoyl phorbol acetate results in chromosomal DNA fragmentation in Raji BL cells.70 Such oncolytic therapy has been used to sensitise EBV+ cancer cells to anti-EBV drugs and is a potential therapeutic strategy.

Although no drug has been licensed for the treatment of EBV infection, there are a variety of antiviral and other drugs, as well as vitamins and plant extracts which effectively inhibit EBV replication (table 1 and figure 1). In each case, the anti-EBV activity is directed toward the prevention of replication, and none has any effect on the latent phase of infection.

Anti-herpesvirus drugs

Aciclovir is a nucleoside analogue approved for the treatment of herpes simplex virus (HSV) and VZV infections. The antiviral effect of aciclovir is mediated by the interaction of aciclovir triphosphate with herpesvirus DNA polymerase with much higher affinity than for cellular polymerases. Aciclovir triphosphate is incorporated into the viral DNA where it irreversibly stops chain elongation. Anti-EBV activity of aciclovir is significantly less than its activity against HSV and VZV. Aciclovir is not clinically useful in EBV-associated IM, but it has been shown to reduce EBV shedding.24 25

Ganciclovir (dihydroxypropoxymethyl guanine) exhibits greater anti-EBV activity than aciclovir, but it is much more toxic which makes it use in otherwise normal persons more difficult to justify.74 Valganciclovir is the L-valyl ester of ganciclovir which is metabolised to ganciclovir by the intestine and liver following oral administration. Valganciclovir is licensed for the treatment of CMV disease and has been shown to significantly reduce the level and duration of EBV shedding in IM in a randomised, double-blind, placebo-controlled study.74

Omaciclovir (H2G) is a carbocyclic analogue of aciclovir which is active against several herpesviruses and has good anti-EBV activity.75 Valomaciclovir is a L-valine ester of H2G, with higher oral bioavailability. Valomaciclovir was the subject of a clinical trial in IM and was shown to mediate faster clinical improvement than placebo recipients, although the effect was not statistically significant. Valomaciclovir significantly decreased EBV load in the mouth, compared with placebo (ClinicalTrials.gov trial: NCT00575185).

Maribavir (MBV) is an investigational oral benzimidazole L-ribose with significant activity against CMV and EBV, mediated by an effect on the protein kinases. MBV inhibits EBV through a unique dual effect of inhibition of viral DNA replication and viral transcription.76

Cidofovir ((S)−1-(3-hydroxy-2-phosphonylmethoxypropyl) cytosine) is a nucleoside analogue which has been used for the treatment of human papillomavirus-associated lesions.77 Cidofovir has been shown to have an antiproliferative effect although the mechanism of this is not understood. Cidofovir has also been shown to inhibit the growth of EBV+ NPC xenografts in nude mice.79 80

Other drugs with anti-EBV activity

Cimetidine was the first H2 antagonist and has multiple anti-cancer activities including antiproliferative activity on cancer cells, immunomodulatory effects, effects on cell adhesion and antiangiogenic activity. Histamine is associated with an immunosuppressive tumour microenvironment through an increase in CD4+CD25+ regulatory T cell activity, reduced antigen-presenting activity of dendritic cells (DCs), reduced NK cell activity and increased myeloid-derived suppressor cell activity.81 82 Cimetidine therapy has been reported anecdotally to benefit patients with chronic EBV reactivation.83 84 Although this has not been studied formally in clinical trials. Possible mechanisms include inhibition of the T helper suppressor cell, resulting in potentiation of cytotoxicity of CD8+ T cells, and antiproliferative activity.81 82 85

Antiretroviral drugs have been reported, in several reports, to induce prolonged remission in MS.86–88 These patients were taking zidovudine and lamivudine,36 efavirenz/emtricitabine/tenofovir-disoproxil fumarate (ATRIPLA)87 and emtricitabine/tenofovir and nelfinavir.38 3’-Azido-3’-deoxythymidine (Zidovudine) was shown to inhibit EBV replication in vitro in P3HR-1 cells.88 L(-)FMAU (Clevudine), L(-)I-OddC and Br(-)Br-OddU have also been shown to exhibit anti-EBV replication activity.90

Valpromide is an amide derivative of valproic acid, which unlike valproic acid, inhibits the expression of BRLF1 and BZLF1 and is not a histone deacetylase (HDAC) inhibitor and so does not alter the expression of several other cellular immediate-early genes which are induced by HDAC inhibitors in cells refractory to EBV lytic induction. Therefore, valpromide inhibits both viral and cellular genes involved in EBV lytic infection.91

Bromodomain and extraterminal family members block two different steps in the sequential cascade of the lytic EBV cycle.
First, they prevent the expression of the EBV immediate-early gene, BZLF1. JQ1 reduces transcription of BZLF1 through an effect on genes controlled by host protein BACH1, and BACH1 knockdown reduces BZLF1 expression. JQ1 also localises to the effect on genes controlled by host protein BACH1, and BACH1 gene, BZLF1. JQ1 reduces transcription of BZLF1 through an inducible nitric oxide synthase.

Artesunate is known to inhibit herpesvirus replication in both epithelial cells and lymphocytes. Artesunate has been shown to inhibit EBV replication through an effect on genes controlled by host protein BACH1, and BACH1 knockdown reduces BZLF1 expression. JQ1 also localises to the effect on genes controlled by host protein BACH1, and BACH1 gene, BZLF1. JQ1 reduces transcription of BZLF1 through an inducible nitric oxide synthase.

Table 1: Therapeutic inhibitors of EBV reactivation and replication

<table>
<thead>
<tr>
<th>Inhibitor of EBV reactivation</th>
<th>Mechanism of action</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aciclovir</td>
<td>Aciclovir triphosphate is a specific inhibitor of herpesvirus DNA polymerase leading to obligate chain termination.</td>
<td>74</td>
</tr>
<tr>
<td>Ganciclovir/valganciclovir</td>
<td>Preferential inhibitor of herpesvirus DNA polymerase and competitive inhibitor of dGTP incorporation into DNA.</td>
<td>75</td>
</tr>
<tr>
<td>Omaciclovir (H2G)/valomaciclovir</td>
<td>H2G triphosphate is a specific inhibitor of herpesvirus DNA polymerase leading to limited chain elongation.</td>
<td>76</td>
</tr>
<tr>
<td>Maribavir</td>
<td>Oral benzimidazole-L-riboside which inhibits HCMV and EBV protein kinases.</td>
<td>77</td>
</tr>
<tr>
<td>Cidovir</td>
<td>Cidovir diphosphate selectively inhibits viral DNA polymerase.</td>
<td>78-80</td>
</tr>
<tr>
<td>Other drugs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cimetidine</td>
<td>H₂, antagonist, inhibition of T suppressor cells, cellular proliferation, adhesion and angiogenesis.</td>
<td>81-85</td>
</tr>
<tr>
<td>Zidovudine</td>
<td>Thymidine analogue which selectively inhibits HIV reverse transcriptase. Anti-EBV effect not proven or elucidated.</td>
<td>86-88, 90</td>
</tr>
<tr>
<td>Clevudine</td>
<td>Clevudine triphosphate inhibits multiple steps in the intracellular life cycle of hepatitis B virus. Anti-EBV effect not proven or elucidated.</td>
<td>86-89</td>
</tr>
<tr>
<td>Valpromide</td>
<td>Prevention of expression of immediate-early EBV genes, BZLF1 and BRLF1.</td>
<td>91</td>
</tr>
<tr>
<td>JQ1, and bromodomain and extraternal</td>
<td>JQ1 inhibits the growth of EBV+ nasopharyngeal cancer cells; proapoptotic, antiproliferative and enhancement of radiological sensitivity.</td>
<td>92, 93</td>
</tr>
<tr>
<td>Artesunate</td>
<td>Inhibition of immediate-early EBV protein synthesis.</td>
<td>94-95</td>
</tr>
<tr>
<td>H31 sequence-specific inhibitor</td>
<td>Inhibition of EBNA1-dependent OriP sequence-specific DNA-binding activity.</td>
<td>96, 97</td>
</tr>
<tr>
<td>EB2 inhibitor, GSK62753A</td>
<td>Inhibition of oxysterol-induced EB2 activation, β-arrestin recruitment and chemotaxis in B lymphocytes.</td>
<td>98, 99</td>
</tr>
<tr>
<td>EB2 inhibitor, NIB189</td>
<td>EB2 inhibition; blocks migration in U937 monocytes.</td>
<td>100</td>
</tr>
<tr>
<td>Vitamin C</td>
<td>Inhibition of EBV activation in human lymphoblastoid cells. Killing of EBV+ Burkitt lymphoma cells and EBV-transformed cells in vitro.</td>
<td>101-103</td>
</tr>
<tr>
<td>Vitamin D</td>
<td>Direct inhibition of enveloped viruses. Upregulation of antimicrobial peptides LL-37 and human β-defensin. LL-37 may disrupt viral envelope.</td>
<td>104-109</td>
</tr>
<tr>
<td>Retinoic acid</td>
<td>Negative regulator of EBV BZLF1 and thus inhibits EBV lytic cycle. Irreversible inhibition of EBV-transformed B lymphocytes.</td>
<td>110-113</td>
</tr>
<tr>
<td>Dietary constituents and supplements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resveratrol</td>
<td>Inhibition of EBV lytic cycle through effects on multiple molecular targets.</td>
<td>114-116</td>
</tr>
<tr>
<td>Luteolin</td>
<td>Inhibition of promoter activity of EBV immediate-early genes, BRLF1 and BZLF1. Reduces genomic instability and suppresses tumourigenicity of EBV.</td>
<td>117-124</td>
</tr>
<tr>
<td>Apigenin</td>
<td>Inhibition of EBV BRLF1 and BZLF1 activity.</td>
<td>125</td>
</tr>
<tr>
<td>Astragalus extract</td>
<td>Inhibition of expression of BZLF1, BRLF1 and EA-D during EBV lytic cycle.</td>
<td>126</td>
</tr>
<tr>
<td>Epigallocatechin-3-gallate</td>
<td>Downregulation of LMP1. Inhibition of EBV-induced B-lymphocyte transformation via suppression of RelA acetylation. 127-131</td>
<td></td>
</tr>
<tr>
<td>Delta-9-tetrahydrocannabinol (THC)</td>
<td>THC inhibits replication of γ-herpesviruses. Mechanism not understood.</td>
<td>132</td>
</tr>
<tr>
<td>L-arginine</td>
<td>Suppression of EBV replication through enhancement of iNOS and nitric oxide.</td>
<td>133</td>
</tr>
<tr>
<td>Sulforaphane</td>
<td>Inhibition of transactivation of Rta, but not Zta.</td>
<td>134</td>
</tr>
<tr>
<td>Curcumin</td>
<td>Enhanced apoptosis-mediated inhibition of proliferation of EBV-transformed lymphoblastoid cell line. Inhibition of BZLF1 transcription.</td>
<td>135-137</td>
</tr>
<tr>
<td>Baicalein</td>
<td>Inhibition of EBV+ NPC through repression of activity of EBNA1 Q-promoter.</td>
<td>138</td>
</tr>
<tr>
<td>(+)-Rutamarin</td>
<td>Cellular topoisomerase II catalytic inhibitor.</td>
<td>139, 140</td>
</tr>
</tbody>
</table>

EAD, early antigen D; EB2, EBV-induced 2 gene; EBNA1, EBV nuclear antigen 1; EBV, Epstein-Barr virus; HCMV, human cytomegalovirus; NPC, nasopharyngeal carcinoma; iNOS, inducible nitric oxide synthase. 

The human GPCR, EBI2, is a key receptor in B cells, T cells and DCs, modulating the T and B cell response to bloodborne antigens. 98 EB2 is highly upregulated in response to EBV infection. 92 93 T1DM, RA, SLE, MS, CFS/ME and several cancers. 94 95 There are two EB2 modulators in development. GSK62753A is a small molecule, potent EB2 antagonist which blocks 7α-25HC.
Figure 1 Schematic diagram showing Epstein-Barr virus (EBV) latency with B-cell transformation, and the steps comprising the EBV lytic cycle (immediate-early proteins, early proteins, viral genome replication, late (structural) proteins and virion production). The role of cytotoxic CD8+ lymphocytes is also shown responding to the infection, under the influence of Th1 suppressor cells. Numbers 1–8 have been added to the diagram to indicate different mechanisms of action of anti-EBV drugs, vitamins and nutritional supplements. Number 1, inhibition of transcription or function of the immediate-early genes, BZLF1 and BRLF1, which represent the first step in the EBV lytic cycle (valpromide, maribavir, orfivir). Number 2, inhibition of the function of Epstein-Barr nuclear antigen 1 (H31, baicalein). Number 3, inhibition of viral DNA replication through either inhibition of cellular topoisomerases I and II which are required for EBV genome replication (cisplatin, vinylpyrrolizidine). Number 4, inhibition of viral DNA replication through either inhibition of cellular topoisomerases I and II which are required for EBV genome replication (cisplatin, vinylpyrrolizidine). Number 5, inhibition of B-cell transformation (epigallocatechin-3-gallate). Number 6, a cellular antiproliferative effect (retinoic acid, JQ1, cimetidine). Number 7, inhibition of the function of the human G-protein coupled receptor, EBV-induced gene 2 (GSK682753A, NIBR189). Number 8, inhibition of Th1 suppressor cells, resulting in enhanced CD8+ cell cytotoxicity (cimetidine).

stimulation of the EBI2 receptor in a recombinant system.99 NIBR189 is a potent selective antagonist of EBI2, being developed in particular for cardiovascular disease.100

Vitamins with anti-EBV activity

Higher plasma levels of vitamin C have been correlated with lower levels of EBV viral capsid antigen IgM and EA IgG in patients with acute and prolonged symptomatic EBV infection.101 Vitamin C has been shown to kill EBV+ BL cells and EBV-transformed B cells in vitro.102 Vitamin C was found to abrogate EBV activation in human lymphoblastoid cells.103 Vitamin D deficiency occurs with apparent increased frequency in acute IM.104 An inverse correlation was reported between vitamin D status and EBV load but not EBNA1 antibody level in relapsing, remitting MS (RR-MS).105 High-dose oral vitamin D₃ supplementation was shown to lower anti-EBNA1 antibody level in patients with RR-MS.106 Vitamin D levels which reach a nadir during late winter and early spring are correlated with increased disease activity, clinical severity as well as relapse rates in several autoimmune diseases including MS, non-cutaneous flares of SLE, psoriasis and RA.107 The seasonality of infectious disease in general is markedly influenced by sunlight and vitamin D level, which explain the winter peaks of incidence of symptomatic infection with various respiratory viruses.108 109

Retinoic acid is a metabolite of vitamin A1 (all-trans-retinol) which mediates the functions of vitamin A₁ that are required for growth and development and is required in all higher animals. All-trans-retinoic acid binds the retinoic acid receptor (RAR) which modifies transcription of different sets of genes depending on cell type. Retinoic acid is a negative regulator of EBV BZLF1 and thus inhibits EBV reactivation.110 Retinoids have also been shown to irreversibly inhibit in vitro growth of EBV-transformed B lymphocytes,111 through upregulation of the cyclin-dependent kinase inhibitor, p27Kip1.112 This antiproliferative effect has also been demonstrated in EBV-transformed B cells with an activated c-Myc oncogene.113

Nutritional supplements with anti-EBV activity

Resveratrol (3, 5, 4 ′- trihydroxy-trans-stilbene) is a type of natural phenol called a stilbenoid, and a phytoalexin produced by plants as a response to injury or infection. Sources of resveratrol in food include the skin of grapes, blueberries, raspberries, mulberries and peanuts. Resveratrol prevents EBV transformation and inhibits the outgrowth of EBV-transformed B lymphocytes114 and EBV-infected BL cells.115 Resveratrol also inhibits EBV lytic cycle in BL cells through effects on multiple molecular targets.116

Luteolin is a flavone with a flavonoid 2-phenylchromen-4-one ring structure and has a yellow crystalline appearance. Luteolin has also been shown to significantly inhibit EBV reactivation by suppressing promoter activities of two immediate early genes, BRLF1 and BZLF1.117 It also reduces genomic instability and suppresses tumourigenic features induced by repeated EBV reactivation, suggesting that inhibition of EBV reactivation is a novel target to prevent NPC relapse.118 Luteolin is an effective free radical scavenger and inducer of tumour apoptosis119 and has been shown to have valuable anticancer effects.120 It is antiangiogenic, antinematostatic, anti-inflammatory and antioestrogenic, and regulates many signalling pathways.121 122 Luteolin has been shown to have profound antiviral properties.123 124 Natural sources include celery, broccoli, green pepper, parsley, thyme, dandelion, perilla, chamomile, carrots, olive oil, peppermint, rosemary, navel oranges and oregano.

Apigenin (4′, 5, 7-trihydroxyflavone) is a natural product of many plants. It has a yellow crystalline appearance and has been used to dye wool. Apigenin inhibits EBV reactivation through suppression of the activities of two immediate early EBV genes, BRLF1 and BZLF1.125 It is also a potent inhibitor of the enzyme CYP2C9, which metabolises many drugs in the body. It also activates monoamine transporters, is a weak anxiolytic and sedative, is a non-selective antagonist of all three opioid receptors, and may activate monoamine transporters, is a weak anxiolytic and sedative, and thus inhibits EBV reactivation.110 Retinoids have also been shown to irreversibly inhibit in vitro growth of EBV-transformed B lymphocytes,111 through upregulation of the cyclin-dependent kinase inhibitor, p27Kip1.112 This antiproliferative effect has also been demonstrated in EBV-transformed B cells with an activated c-Myc oncogene.113

Polysaccharide extract of the Chinese herb, Astragalus membranaceus, was shown to inhibit EBV reactivation in EBV-infected Raji cells in vitro. Astragalus polysaccharide extract in a non-cytotoxic concentration of 30 µg/mL significantly suppressed the expression of BZLF1, BRLF1 and EA-D during the EBV lytic cycle and is potentially useful as an anti-EBV drug.126

Epigallocatechin-3-gallate (EGCG) is one of the green tea polyphenols and has been shown to inhibit EBV replication127 through ERK1/2 and PI3K/Akt signalling in EBV+ cells,128 also...
A variety of rutamarin derivatives also exhibit similar inhibition of EBV replication, with effective anti-EBV activity, demonstrating the importance of a nutritious diet and a healthy lifestyle in the prevention of EBV reactivation.

**Take home messages**

- Epstein-Barr virus (EBV) infection infects almost everyone in all populations studied.
- EBV persists life-long following acute infection and is reactivated with prolonged psychological stress which weakens cellular immunity.
- EBV reactivation has been associated with various autoimmune diseases, chronic fatigue syndrome/myalgic encephalomyelitis (CFS/ME) and various malignancies.
- Various drugs, vitamins and nutritional supplements inhibit EBV reactivation and several other critical points in the EBV life cycle.
- A nutritious diet containing sufficient vitamins A, C and D is important in the control of EBV infection and prevention of disease.

**Handling editor** Tahir S Pillay.

**Contributors** JRK conceived the idea for this review, performed literature searches and wrote the article without the assistance of any other person.

**Funding** The authors have not declared a specific grant for this research from any funding agency in the public, commercial or not-for-profit sectors.

**Competing interests** None declared.

**Patient consent for publication** Not required.

**Provenance and peer review** Not commissioned; externally peer reviewed.

**REFERENCES**


reactivation of latent Epstein-Barr virus in response to examination stress.

2010;126:NA–89.


et al. Antiviral drugs for EBV. Cancers 2018;10.


et al. Epstein-Barr virus-induced DNA polymerase by a new guanosine analog, 9-


et al. Natural variations in BRLF1 promoter sequence direct B-cell migration through EBI2. Front Pediatr 2016;4:1851–60.


et al. Stress-related activation of Epstein-Barr virus.


84 Cimetidine GI. Ranitidine, and Epstein-Barr virus infection. *Ann Intern Med 1986;105*.
87 Skarlis C, Gontikas M, Katsoyas S, et al. Multiple sclerosis and subsequent human immunodeficiency virus infection: a case with the rare comorbidity, focus on novel treatment issues and review of the literature in vivo (Brooklyn) 2017;31:1041–6.
91 Treatment of viral associated cancers.