(-)-Epigallocatechin-3-gallate inhibition of Epstein–Barr virus spontaneous lytic infection involves ERK1/2 and PI3-K/Akt signaling in EBV-positive cells

Sufang Liu1, Hongde Li1, Lin Chen1, Lifang Yang1, Lili Li2, Yongguan Tao1, Wei Li2, Zijian Li2, Haidan Liu1, Min Tang3, Ann M. Bode3, Zigang Dong3 and Ya Cao*1

1Cancer Research Institute, Xiangya School of Medicine, Central South University, Key Laboratory for Cancer and Invasion of Ministry of Education, Changsha, Hunan 410011, China; 2Division of Hematology, Institute of Molecular Hematology, the Second Xiangya Hospital, Central South University, Changsha, Hunan 410011, China; and 3The Hormel Institute, University of Minnesota, 801 16th Avenue NE, Austin, MN 55912, USA

*To whom correspondence should be addressed. Tel: +86-731-84805448; Email: ycao98@vip.sina.com

Correspondence may also be addressed to Zigang Dong. Tel: +507-437-9600; Fax: +507-437-9606; Email: zgdong@hi.umn.edu

Epstein–Barr virus (EBV) reactivation into the lytic cycle plays certain roles in the development of EBV-associated diseases, including nasopharyngeal carcinoma and lymphoma. In this study, we investigated the effects of the tea polyphenol (-)-epigallocatechin-3-gallate (EGCG) on EBV spontaneous lytic infection and the mechanisms(s) involved in EBV-positive cells. We found that EGCG could effectively inhibit the constitutive lytic infection of EBV at the DNA, gene transcription and protein levels by decreasing the phosphorylation and activation of extracellular signal-regulated kinase 1/2 (ERK1/2) and Akt. By using cellular signaling pathway-specific inhibitors, we also explored the signaling mechanisms underlying the inhibitory effects of EGCG on EBV spontaneous lytic infection in cell models. Results show that specific inhibitors of Mitogen-Activated Protein Kinase Kinase (MEK) (PD98059) and phosphatidylinositol 3-kinase (PI3-K (LY294002)) markedly downregulated gene transcription and expression of BZLF1 and BMRF1 indicating that the MEK/ERK1/2 and PI3-K/Akt pathways are involved in the EBV spontaneous lytic cycle cascade. Therefore, one of the mechanisms by which EGCG inhibits EBV spontaneous lytic infection appears to involve the suppression of the activation of MEK/ERK1/2 and PI3-K/Akt signaling.

Introduction

Epstein–Barr virus (EBV) is a human herpes virus that infects 90% of the human population. EBV infection, as one of many environmental factors, has been reported to be strongly associated with the development of several human malignancies, including Burkitt’s lymphoma, Hodgkin’s disease and nasopharyngeal carcinoma (NPC) (1,2). Importantly, an increasing number of tumors are found to be EBV-positive (3,4). Like all other herpes viruses, EBV can establish a latent infection in cell models. Results show that specific inhibitors of Mitogen-Activated Protein Kinase Kinase (MEK) (PD98059) and phosphatidylinositol 3-kinase (PI3-K (LY294002)) markedly downregulated gene transcription and expression of BZLF1 and BMRF1 indicating that the MEK/ERK1/2 and PI3-K/Akt pathways are involved in the EBV spontaneous lytic cycle cascade. Therefore, one of the mechanisms by which EGCG inhibits EBV spontaneous lytic infection appears to involve the suppression of the activation of MEK/ERK1/2 and PI3-K/Akt signaling.

Abbreviations: AP-1, activator protein; DMSO, dimethylsulfoxide; EBV, Epstein–Barr virus; EGCG, (-)-epigallocatechin-3-gallate; ERK, extracellular signal-regulated kinase; PBS, fetal bovine serum; LMP1, latent membrane protein 1; MAPK, mitogen-activated protein kinase; mRNA, messenger RNA; MTT, 3-(4,5-dimethylthiazole-2-yl)-2,5-diphenyltetrazolium bromide; NPC, nasopharyngeal carcinoma; PBS, phosphate-buffered saline; PI3-K, phosphatidylinositol 3-kinase; qPCR, quantitative PCR

Materials and methods

Cell lines and cell culture

B95.8, an EBV-positive mammoset B-cell line, and Raji, an EBV-positive lymphoblast-like cell line established from Burkitt’s lymphoma, were obtained from the American Type Culture Collection. CNE1-LMP1 is a stable LMP1-integrated NPC cell line (20,21). All cells were cultured in RPMI 1640 (Gibco

© The Author 2012. Published by Oxford University Press. All rights reserved. For Permissions, please email: journals.permissions@oup.com
Fig. 1. Detection of EBV-encoded proteins and EBV DNA in cells. (A) Cells were disrupted and immunoblot analysis was performed to determine the expression of EBNA1, LMP1, BZLF1 and BMRF1. (B) CNE1-LMP1 cells were fixed in 4% paraformaldehyde and permeabilized with 0.1% Triton X-100. BZLF1 or BMRF1 was visualized with mouse monoclonal anti-BZLF1 (1:100) or anti-BMRF1 (1:100) and a fluorescein isothiocyanate-conjugated secondary antibody (1:200). Incubation with PBS but no primary antibody and then with secondary antibody was used as a negative control. DNA was stained with DAPI.

EBV copies (copies/50 ng DNA)

CNE1-LMP1 B95.8

*
EGCG inhibits EBV lytic infection

BRL, Grand Island, NY), supplemented with 10% fetal bovine serum (FBS; Invitrogen, Carlsbad, CA), 10 µg/ml streptomycin and 100 IU/ml penicillin, and incubated in a humidified atmosphere of 5% CO₂ at 37°C.

**Chemicals and cell treatments**

EGCG and LY294002 were purchased from Sigma Chemical (St Louis, MO), and PD98059 was purchased from Calbiochem (La Jolla, CA). EGCG and all inhibitors were prepared in autoclaved water and dimethylsulfoxide (DMSO; Sigma), respectively, as stock solutions for in vitro studies. Subconfluent cells were treated with the respective compounds at various concentrations for different times as indicated. Detailed treatment procedures are described in the Figure Legend 4. The final concentration of DMSO in the culture media was maintained at <0.1%, which had no significant effect on cell growth. Vehicle controls were included for all treatments.

**Preparation of cell lysates and immunoblot analysis**

Whole cell lysate preparation and immunoblot analysis were performed according to the method described previously (11). Protein concentration was determined using the BCA Assay Reagent (Pierce, Rockford, IL). The following antibodies were used for immunodetection with appropriate dilutions: mouse BZLF1 monoclonal antibody (AZ-69; Argene, Varilhes, France), EBNA1 antibody (ab25653; Abcam, Cambridge, UK), BMRFI antibody (ab6524; Abcam), β-actin (Ac-15; Sigma), Akt antibody (9272; Cell Signaling Technology, Danvers, MA) and p-Akt (Ser473) (9271; Cell Signaling Technology). The -actin (Ac-15; Sigma), Akt antibody (9272; Cell Signaling Technology, Danvers, MA) and p-Akt (Ser473) (9271; Cell Signaling Technology, Danvers, MA) and p-Akt (Ser473) (9271; Cell Signaling Technology). The antibodies against ERK1 (sc-93), p-ERK (Tyr-204) (sc-7383), goat anti-rabbit IgG-horseradish peroxidase (sc-2004) and goat anti-mouse IgG-horseradish peroxidase (sc-2005) were all from Santa Cruz (Santa Cruz, CA).

**Immunohistochemistry**

Thirty-three paraffin-embedded NPC tissues and 24 paraffin-embedded lymphoma tissues (Hodgkin’s lymphoma (19), Burkitt’s lymphoma (4) and NHL (1)) were obtained from the Department of Pathology at Hunan Tumor Hospital and Xiangya Hospital, Changsha, China. Immunohistochemistry was performed on 4.0 µm sections from formalin-fixed, paraffin-embedded tissues. The sections were deparaffinized and rehydrated. Antigen retrieval was achieved with diluted ethylenediaminetetraacetic acid (50:1) by microwaving for 10 min. Endogenous peroxidase activity was quenched with a 3% hydrogen peroxide block for 15 min at room temperature. The sections were treated with goat serum for 10 min and incubated at 4°C overnight with the primary antibody (BZLF1 diluted 1:100). The secondary antibody, biotinylated horse anti-mouse IgG (Vector Laboratories, Burlingame, CA) diluted 1:200 was applied for 30 min at 37°C; followed by a 30 min incubation with Vectastain ABC Elite. The reaction was visualized by using diaminobenzidine chromogen (Dako) following the manufacturer’s instructions, and the slides were counterstained with Mayer’s hematoxylin. All slides were scored by two observers. The staining intensity and pattern were evaluated using a 0 to 3+ scale (0, completely negative; 1+, weak; 2+, intermediate; 3+, strong). A final score ≥2+ or greater was required for the case to be considered positive.

**MTT assay**

The 3-(4,5-dimethylthiazole-2-yl)-2,5-diphenyltetrazolium bromide (MTT) assay was used to assess the effects of EGCG on cell viability as described previously (22). Briefly, cells were cultured in 96 well flat-bottomed plates and were starved in 0.1% FBS RPMI medium 1640 for 24h. Then, serial dilutions of EGCG were added to the cells and incubated for the indicated time. Following the incubation period, 10 µl MTT (5 mg/ml) per well was added and then incubated for another 4h at 37°C. After discarding the medium, 150 µl DMSO was added to each well and mixed thoroughly to dissolve the blue formazan crystals. The plates were subsequently read on a Bio-Rad 3350 microplate reader at a wavelength of 570 nm. Null control wells contained medium alone. Cell viability was calculated as the percentage of MTT inhibition using the following formula: viability (%) = (OD<sub>blank</sub> treatment – OD<sub>blank</sub> no treatment control) / (OD<sub>blank</sub> no treatment control × 100%). The experiments were repeated at least three times.

---

Fig. 2. Immunohistochemical staining for EBV lytic proteins in specimens from patients with NPC and lymphoma. Paraffin sections were screened for the expression of the EBV lytic proteins with the specific antibodies to detect BZLF1 and BMRFI. Positive signal implies that BZLF1 or BMRFI expression occurs in tumor cells as shown by nuclear localization in different cases. Magnification, ×400.

**Table 1.** The final concentration of DMSO in the culture media was maintained at <0.1%, which had no significant effect on cell growth. Vehicle controls were included for all treatments.

**Preparation of cell lysates and immunoblot analysis**

Whole cell lysate preparation and immunoblot analysis were performed according to the method described previously (11). Protein concentration was determined using the BCA Assay Reagent (Pierce, Rockford, IL). The following antibodies were used for immunodetection with appropriate dilutions: mouse BZLF1 monoclonal antibody (AZ-69; Argene, Varilhes, France), EBNA1 antibody (ab25653; Abcam, Cambridge, UK), BMRFI antibody (ab6524; Abcam), β-actin (Ac-15; Sigma), Akt antibody (9272; Cell Signaling Technology, Danvers, MA) and p-Akt (Ser473) (9271; Cell Signaling Technology). The antibodies against ERK1 (sc-93), p-ERK (Tyr-204) (sc-7383), goat anti-rabbit IgG-horseradish peroxidase (sc-2004) and goat anti-mouse IgG-horseradish peroxidase (sc-2005) were all from Santa Cruz (Santa Cruz, CA).

**Immunohistochemistry**

Thirty-three paraffin-embedded NPC tissues and 24 paraffin-embedded lymphoma tissues (Hodgkin’s lymphoma (19), Burkitt’s lymphoma (4) and NHL (1)) were obtained from the Department of Pathology at Hunan Tumor Hospital and Xiangya Hospital, Changsha, China. Immunohistochemistry was performed on 4.0 µm sections from formalin-fixed, paraffin-embedded tissues. The sections were deparaffinized and rehydrated. Antigen retrieval was achieved with diluted ethylenediaminetetraacetic acid (50:1) by microwaving for 10 min. Endogenous peroxidase activity was quenched with a 3% hydrogen peroxide block for 15 min at room temperature. The sections were treated with goat serum for 10 min and incubated at 4°C overnight with the primary antibody (BZLF1 diluted 1:100). The secondary antibody, biotinylated horse anti-mouse IgG (Vector Laboratories, Burlingame, CA) diluted 1:200, was applied for 30 min at 37°C; followed by a 30 min incubation with Vectastain ABC Elite. The reaction was visualized by using diaminobenzidine chromogen (Dako) following the manufacturer’s instructions, and the slides were counterstained with Mayer’s hematoxylin. All slides were scored by two observers. The staining intensity and pattern were evaluated using a 0 to 3+ scale (0, completely negative; 1+, weak; 2+, intermediate; 3+, strong). A final score ≥2+ or greater was required for the case to be considered positive.

**MTT assay**

The 3-(4,5-dimethylthiazole-2-yl)-2,5-diphenyltetrazolium bromide (MTT) assay was used to assess the effects of EGCG on cell viability as described previously (22). Briefly, cells were cultured in 96 well flat-bottomed plates and were starved in 0.1% FBS RPMI medium 1640 for 24 h. Then, serial dilutions of EGCG were added to the cells and incubated for the indicated time. Following the incubation period, 10 µl MTT (5 mg/ml) per well was added and then incubated for another 4 h at 37°C. After discarding the medium, 150 µl DMSO was added to each well and mixed thoroughly to dissolve the blue formazan crystals. The plates were subsequently read on a Bio-Rad 3350 microplate reader at a wavelength of 570 nm. Null control wells contained medium alone. Cell viability was calculated as the percentage of MTT inhibition using the following formula: viability (%) = (OD<sub>blank</sub> treatment – OD<sub>blank</sub> no treatment control) / (OD<sub>blank</sub> no treatment control × 100%). The experiments were repeated at least three times.
Transgenic transfection and luciferase assay

Cells were seeded in 24-well plates before transfection. pZip-Luc (kindly provided by Ichiro Saito, Tsurumi University School of Dental Medicine, Yokohama, Japan) (23) or pMP-Luc (kindly provided by Paul J. Farrell, Imperial College Faculty of Medicine, London, UK) (24) was cotransfected with an internal control pRL-SV40 using the Lipofectamine 2000 Transfection Reagent (Invitrogen) following the manufacturer’s instructions. At 4h after transfection, cells were treated with chemicals as designated. Cells were harvested at 24h after transfection and lysates were analyzed for luciferase activity using the Dual Luciferase Reporter Assay (Promega, Madison, WI) according to the manufacturer’s directions. The luciferase reporter plasmids were cotransfected with pRL-SV40 to correct for variations in transfection efficiency. The relative luciferase activity was normalized to the value of pRL-SV40 activity. The data are represented as means ± SD of three independent experiments performed in triplicate.

RT-PCR and qPCR

Total RNA from cultured cells was isolated using TRIzol following the manufacturer’s instructions (Invitrogen). Complementary DNA was synthesized using 1–5 µg of purified RNA, the RevertAid™ First Strand cDNA Synthesis Kit (Fermentas, EU) and Oligo(dT) (sense) complementary DNA with the following primers: 5′-CATGTTTCAACCGβGGAGCAAT-3′ (antisense); pRL-SV40 was transfected into the cell model and also as a positive control. To determine the EBV presence and lytic infection in NPC cell model, we used RT–PCR to quantify EBV DNA load and EBV latency-associated gene expression is consistently detected in NPC cell lines and lymphomas (27,28). B95.8 cell line is a well-known EBV-positive cell line, which is permissive for virus lytic replication. In this study, B95.8 cells were used as the cell model and also as a positive control. To determine the EBV presence and lytic infection in NPC cell model, we used RT–PCR to quantify EBV DNA load and immunofluorescence to analyze the EBV-associated lytic proteins.

First, the EBV latent and lytic proteins were examined using monoclonal antibodies. Immunoblot analysis revealed a constitutive expression of EBV latent proteins, EBNA1 and LMP1, and lytic infection gene products, BZLF1 and BMRF1 (Figure 1A). The expression level of EBV proteins, LMP1, EBNA1, BZLF1 and BMRF1, in B95.8 cells was more notable than in CNE1-LMP1 cells. Immunofluorescence staining

Fig. 3. EGCG reduces the viability of CNE1-LMP1 and B95.8 cells in time- and dose-dependent manners. After starving with 0.1% FBS, cells were treated with EGCG, and then, cell viability was measured by MTT assay. In each treatment group, cells treated with medium serve as a control and their viability was set at 100%. Values are expressed as means ± SD of three experiments (n = 3).
EGCG inhibits EBV lytic infection

A

CNE1-LMP1 cells

B95.8 cells

Relative luciferase activity

Fold induction

EGCG (µM)

BZLF1-reporter

BMRF1-reporter

EGCG (µM)

BZLF1-reporter

BMRF1-reporter

B

CNE1-LMP1

B95.8

EGCG (µM)

0 5 10 20

BZLF1 mRNA level

BMRF1 mRNA level

0 5 10 20

0 5 10 20

C

CNE1-LMP1

B95.8

EGCG (µM)

0 5 10 20

BMRF1

BZLF1

β-Actin

D

CNE1-LMP1 cells

B95.8 cells

Negative control 0.33%

EGCG 20 µM 27.35%

EGCG 0 µM 73.65%

Negative control 2.13%

EGCG 20 µM 78.99%

EGCG 0 µM 96.54%

Negative control 0.33%

EGCG 20 µM 2.89%

EGCG 0 µM 18.57%

Negative control 0.47%

EGCG 20 µM 40.37%

EGCG 0 µM M1 68.99%
revealed that the CNE1-LMP1 cells constitutively expressed the BZLF1 and BMRF1 proteins (Figure 1B). For quantification of EBV copy number, a RT–PCR assay targeting the BamHI-W segment of the EBV genome was developed. The BamHI-W assay has been reported to be more sensitive and suitable than EBER for applications in EBV detection, presumably because it targets a reiterated sequence that is present at approximately 10 copies per EBV genome (29). We used the DNA from Raji cells that contain 50 copies per cell (30). A 10-fold serial dilution of the reference was used as a standard of the viral DNA number. The estimation of viral genomes in each sample was expressed as the number of viral genomes copy per 50 ng of purified DNA. Experiments were performed at least twice to improve reliability of the results. We observed for 24 h and then cultured with different concentrations of EGCG for 24–48 h. 

The inhibitory effect of EGCG on EBV spontaneous lytic infection

The viability of CNE1-LMP1 cells and B95.8 cells after treatment with EGCG was assessed by MTT assay. EGCG exhibited dose- and time-dependent inhibitory effects on these cells with an IC_{50} of 20 μM (Figure 5). Thus, the concentrations of EGCG (5–20 μM) were the doses chosen for subsequent experiments.

To characterize the effect of EGCG on EBV spontaneous lytic infection in cells, a transient transfection assay was performed using a BZLF1 and BMRF1 promoter/luciferase reporter system. Results showed that EGCG effectively suppressed the transcription activity of the BZLF1 and BMRF1 genes in both CNE1-LMP1 and B95.8 cells in a dose-dependent manner (Figure 4A). The effect of EGCG on the mRNA level of EBV spontaneous lytic genes was measured using RT–qPCR. In accordance with the results from transfection assay, the mRNA expression levels of the lytic genes, BZLF1 and BMRF1, were also strongly reduced after EGCG treatment (Figure 4B).

Involvement of the MEK/ERK1/2 and PI3-K/Akt pathways in EGCG’s inhibition of EBV lytic infection

The MEK/ERK1/2 and PI3-K/Akt signaling pathways were reported to play certain roles in EBV lytic replication, and EGCG was shown to suppress the activities of these pathways (18). Thus, we hypothesized that EGCG inhibits EBV spontaneous lytic infection by suppressing these signaling pathways. First, using phospho-specific
EGCG inhibits EBV lytic infection

Fig. 5. Inhibitory effects of EGCG on activation of ERK1/2 and Akt in CNE1-LMP1 and B95.8 cells. (A) Effect of EGCG on phosphorylation of ERK1/2 and Akt. The cells were starved in 0.1% FBS RPMI medium 1640 for 24 h and then cultured with different concentrations of EGCG for 24 h. Cells were then disrupted and immunoblot analysis was performed. (B) In vitro kinase assays of ERK1/2 and Akt were used to evaluate the effects of EGCG. Cells were starved in 0.1% FBS RPMI medium 1640 for 24 h and then cultured with different concentrations of PD98059 and LY294002 for 24 h. Cells were then disrupted and subjected to immunoblot analysis as described in Materials and methods. To ensure that equal amounts of ERK or Akt were immunoprecipitated, we also immunoblotted the precipitate for total ERK or Akt.

antibodies against ERK1/2 and Akt, we found that the phosphorylation of these kinases was suppressed by EGCG (Figure 5A). ERKs or Akt kinase activity was estimated using an ERK kinase assay kit or an Akt kinase assay kit. ERK or Akt was first immunoprecipitated from cell extracts and then incubated with their specific substrate, Elk-1 or GSK-3 fusion protein, respectively, in the presence of adenosine triphosphate and kinase buffer. ERKs- or Akt-dependent Elk-1 or GSK-3 phosphorylation was then measured by immunoblotting using a phospho-antibody that recognizes Elk-1 or GSK-3 when phosphorylated. The kinase assays further confirmed that the activation of ERK1/2 and Akt was inhibited by EGCG in a dose-dependent manner (Figure 5B). These data indicate that EGCG suppresses the activation of the ERK1/2 and Akt signaling pathways.

To determine if the ability of EGCG to inhibit the ERK1/2 and PI3-K/Akt pathways plays a role in the attenuation of EBV lytic infection, a pharmacological approach was adopted using each kinase-specific inhibitor. PD98059, a specific inhibitor of MEK1 that acts by inhibiting activation of ERK1/2, and LY294002, a specific inhibitor of PI3-K that acts by inhibiting activation of Akt, were tested for their effects on EBV lytic infection. Our results showed that treatment of cells with each of these inhibitors dramatically decreased the phosphorylation levels of ERK1/2 and Akt. In addition, these inhibitors suppressed the expression of the EBV lytic proteins in a dose-dependent manner (Figure 6A and B). A transient transfection assay performed using a BZLF1 and BMRF1 promoter/luciferase reporter system showed that the inhibitors each effectively and significantly suppressed the transcription activity of the BZLF1 and BMRF1 genes in our cell models in a dose-dependent manner (Figure 6C and D, P < 0.05).

Next, to determine the inhibitory effect of the inhibitors on EBV lytic gene expression due to the suppressive effects on the genes at the mRNA level, we performed qPCR to estimate BZLF1 and BMRF1 mRNA expression after PD98059 or LY294002 treatment. Consistent with the data from the transfection assay and immunoblot analysis, the qPCR results showed that the inhibitors each effectively and significantly suppressed the mRNA expression of the BZLF1 and BMRF1 genes in a dose-dependent manner (Figure 6E and F, P < 0.05).

Overall, these results indicated that the MEK/ERK1/2 and PI3-K/Akt signaling pathways are involved in EGCG inhibition of EBV spontaneous lytic infection in both CNE1-LMP1 and B95.8 cells.

Discussion

The life cycle of EBV includes latent and lytic stages. In most asymptomatic carriers of EBV, the cells containing latent viral genomes are periodically reactivated to the lytic cycle. Previous studies focused on the effects of EBV latent infection and revealed that viral LMP1 is an oncoprotein (19). But much of the literature points to the fact that EBV
EGCG inhibits EBV lytic infection

EGCG inhibits EBV lytic infection

Fig. 6. Inhibitory effects of PD98059 and LY294002 on EBV spontaneous lytic infection in CNE1-LMP1 and B95.8 cells. Cells were starved in 0.1% FBS RPMI medium 1640 and then cultured with different concentrations of PD98059 or LY294002 for 24 h. (A and B) Cells were then disrupted and immunoblot analysis was performed to determine the expression of total and phosphorylated kinases and lytic proteins. β-Actin was used to verify equal protein loading. (C and D) Effects of PD98059 and LY294002 on the transactivation activity of BZLF1 and BMRF1 were determined using transient transfection and luciferase reporter assays. The relative luciferase activity was normalized to the value of the internal control plasmid pRL-SV40 activity. (E and F) RT–PCR quantification of mRNA expression levels for the BZLF1 and BMRF1 genes. The mRNA level in vehicle cells was set to 1. The data indicate significant decrease in PD98059- or LY294002-treated EBV lytic gene mRNAs. Control treatments were with vehicle (DMSO). Statistical significance:*P < 0.05 versus DMSO.

spontaneous lytic replication takes place in various EBV-associated tumors (8–10). Our results also indicated that the EBV spontaneous lytic infection exists in NPC and lymphoma cells (Figure 1).

Although the lytic protein BZLF1 can induce the viral replication cycle and subsequent cell death, accumulating evidence indicates that expression of BZLF1 does not always result in virus production and cell death. The abortive lytic infection occurs not only in NPC but also in Hodgkin’s disease, non-Hodgkin lymphoma in an immunocompromised host and EBV-associated gastric cancer (28,31–33). Our results also showed that the basal level of early gene BMRF1 in gene transcription and protein expression was much lower than the immediate-early gene BZLF1 (Figures 1A and 4). In addition, the results from immunohistochemistry showed that the percentage of BZLF1-positive cells in NPC and lymphoma biopsies was much larger than the percentage of BMRF1-positive cells (Figure 2). The findings of our study imply that abortive lytic infection may occur in NPC and lymphoma.

Viral lytic genes, such as BZLF1, BMRF1, or cellular genes induced by viral lytic proteins could potentially encode paracrine factors that promote tumor growth. BZLF1 has been reported as having various malignancy-promoting actions (34). BZLF1 has the potential to create the best cellular environment for EBV replication by suppressing the cell-mediated immunity of the host (35,36), regulating the expression of the cellular proteins and the activities of signaling pathways (34,37,38), manipulating the cell cycle (38,39) and interacting with host proteins physically (40,41).

NPC is known to be closely associated with EBV infection, several retrospective and prospective investigations suggest that EBV lytic infection might also play a substantial role in pathogenesis. Elevated antibody titers against EBV lytic antigens, representing EBV lytic infection in vivo, correspond with advanced cancer stages, poor prognosis or tumor recurrence of NPC (6,7). The serologic marker of EBV reactivation into lytic infection also serves as a risk factor of NPC (42). In addition, the presence of lytic viral genome and lytic gene products, such as BZLF1, further supports the notion that EBV replication do occur in some cases (43). The presence of lytic viral genome and lytic gene products, such as BZLF1, also occurs in lymphomas (27). EBV reactivation into lytic EBV gene expression contributes to EBV-associated lymphoproliferative disease, potentially through induction of paracrine B-cell growth factors. BZLF1-induced IL-13 production facilitates B-cell proliferation and may contribute to the pathogenesis of EBV-associated lymphoproliferative disorders, such as post-transplantation lymphoproliferative disease and Hodgkin’s lymphoma (44). A recent study showed the ability of methotrexate (MTX), which is used in patients with rheumatoid arthritis and polymyositis, to increase the level of lytic infectious EBV in patients. This, combined with its potent immunosuppressive effects, may collaborate to induce EBV-positive lymphomas (45). Our data confirm that EBV lytic infection proteins are present not only in NPC and lymphoma cell lines but also in patient biopsies, consistent with the previous studies.

The above evidence has challenged the traditional concept that EBV only transforms cells in its latent infection and has also broadened our knowledge regarding the mechanism of EBV-associated carcinogenesis. By increasing the horizontal transmission of the virus
from cell to cell, EBV lytic infection might increase the total number of latently infected cells. In addition, important implications of EBV lytic infection might include the idea that the infected host cells or nearby cells are transformed, or that the biologic characteristics of these cells might be changed and the degree of malignancy may increase along with the ease with which metastasis can occur. Thus, if EBV lytic infection is inhibited, the potential of the malignancy in the infected cells might be suppressed or reversed.

Cancer chemoprevention by the natural compound, EGCG, has been studied by many investigators and has received much attention in recent years. The inhibitory effects of EGCG against carcinogenesis at different organ sites have been demonstrated in many animal models (16,46). Several studies have shown that EGCG can inhibit EBV lytic infection, but the mechanism involved in the control of EBV gene expression by EGCG is not well understood. Choi et al. (47) found that EBV-induced B-cell outgrowth and B lymphocyte transformation was dramatically inhibited by treatment with EGCG (50 µM), supporting the important role of acetylation in cancer initiation and progression. Taniguchi et al. (48) and Chang et al. (49) demonstrated that EGCG blocks EBV lytic cycle induced by chemicals in Burkitt’ lymphoma cell lines. However, in recent years, considerable progress has been made in the mechanisms of cancer chemoprevention by EGCG. In our studies, we used the NPC cell line (CNE1-LMP1) and lymphoblastoid cell line (B95.8) with EBV spontaneous lytic replication that mimics the natural state of the infected cells. We found that EGCG inhibits EBV spontaneous lytic replication without any inducer and involving the inhibition of the activation of MEK/ERK1/2 and PI3-K/Akt signaling.

EGCG exerts its anticancer effect by modulating a wide spectrum of molecular targets, thus inhibiting tumor development and progression. Located at the cell membrane, EGCG suppresses the activation of multiple receptor tyrosine kinases, including epidermal growth factor receptor, insulin-like growth factor-I receptor and vascular endothelial growth factor receptor. It also inhibits downstream cytoplasmic signaling molecules, such as Akt and ERK1/2, ultimately leading to the abnormalities of certain transcription factors, including nuclear factor-kappaB and activator protein (AP-1) (46,50,51). The BZLF1 gene promoter contains the ZII element, an important positive regulator of Z transcription (52), which has been shown to bind with multiple transcription factors, including CREB, ATF1, ATF2 and AP-1, c-Jun phosphorylation, the main component of AP-1, activates Z transcription through the ZII element (37). We also previously reported that EGCG inhibited the phosphorylation of c-Jun (17,53). Thus, EGCG may disrupt EBV lytic infection-related signaling pathways by directly or indirectly binding to receptors or other target proteins, such as Akt or ERK1/2, and induce the transcription repression of BZLF1 by inhibiting the activation of transcription factor AP-1, thus contributing to EBV lytic infection.

The concept of targeted biological therapy against cancer has emerged over the past decade. Clinical trials studying the efficacy and tolerability of various targeted agents have shown that most tumors depend on more than one signaling pathway for their continued growth and survival. Therefore, investigators pursue different strategies to inhibit multiple signaling pathways by developing multi-targeted agents (54). Large amounts of encouraging data from in vitro and animal models have emerged suggesting that green tea is nature’s gift molecule endowed with anticancer effects. Epidemiological and geographical observations suggest that these laboratory data might be applicable in the human population. The various effects of green tea polyphenols and especially EGCG clearly seem to have the ability to be utilized in the multi-targeted therapy of cancer (55).

During the course of studying the effects of EGCG on regulating different key proteins in various signaling pathways, the direct interaction of proteins with EGCG was found to be a key step in the process of EGCG exerting its effects. The identification of proteins interacting directly with EGCG is important in understanding the molecular mechanisms of the effects of EGCG. Several proteins that can directly bind with EGCG have been identified and include laminin, GRP-78, insulin-like growth factor-I receptor, G3BP1, ZAP-70 and vimentin (56). In summary, this study presented novel experimental evidence describing the mechanisms underlying the inhibition of EBV spontaneous lytic replication by EGCG in both epithelial NPC and B-cell lymphoma models. Our findings support the future investigation of EGCG as an anti-cancer and chemoprevention agent for EBV-associated malignancies. Further study regarding the inhibitory effect of EGCG on EBV lytic infection in vivo is needed.

**Funding**

National Nature Science Foundation of China (No. 81101474, 81072220 and 8116120410); State Key Basic Research and Development Plan (973) of the Ministry of Science and Technology of China (No. 2011CB504300); the Joint Research Fund of National Nature Science Foundation (No. R37CA081064).

**Acknowledgements**

We thank Weivei Wang, Faqing Tang from Xiangya Hospital of Central South University and Liang Zeng from Hunan Tumor Hospital for technical support; Ming Li from the Basic Medical School of the Central South University for helpful comments. We thank Dr Ichiro Saito for the gift of the pZp-Luc plasmid and Dr Paul J.Farrell for the gift of the pMP-Luc plasmid. We also thank Dr Ann M.Bode from The Hormel Institute of University of Minnesota for critical reading of this manuscript.

Conflict of Interest Statement: None declared.

**References**

EGCG inhibits EBV lytic infection


Received March 22, 2012; revised October 8, 2012; accepted November 8, 2012