

## Blimp-1 Expression as an Exhaustion Transcription Factor in Chronic Lymphocytic Leukemia

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### Abstract

**Background:** Previously, it was shown that exhausted CD4+ and CD8+ T cells in chronic lymphocytic leukemia (CLL) co-express the two immune-inhibitory receptors, Tim-3 and PD-1. Present study investigated the expression of Blimp-1, a transcription factor involved in T cell exhaustion, in patients with CLL.

**Materials and Methods:** Peripheral blood mononuclear cells were collected from 25 untreated CLL patients and 15 sex- and age-matched normal subjects. CLL patients were clinically classified according to the Rai staging system. The relative expression of Blimp-1 mRNA was determined by quantitative Real Time Polymerase Chain Reaction (qRT-PCR) after normalization with  $\beta$ -actin.

**Results:** Expression of Blimp-1 mRNA was much higher in CLL patients than in normal controls ( $p=0.001$ ). Moreover, Blimp-1 was more expressed in patients with advanced clinical stages of CLL compared to those with early stages of the disease ( $p=0.01$ ). Interestingly, the Blimp-1 expression was correlated with the frequencies of exhausted Tim-3+/PD-1+/CD4+ and Tim-3+/PD-1+/CD8+ T cells in CLL patients.

**Conclusion:** Our results highlight the role of Blimp-1 transcription factor in T cell exhaustion of CLL.

**Keywords:** Exhausted T cell; Blimp-1; Chronic Lymphocytic Leukemia

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### Introduction

Based on the tumor immune-surveillance theory, various components of the immune system constantly survey the body for any malignant cell proliferation and eliminate or slow their growth (1). This theory suggests that both innate and adaptive immunity can respond, recognize, and destroy the malignant cells. However, to escape from the immune system mechanisms, cancerous cells induce an immunosuppressive state in the host (2, 3). One of the well-known immunosuppressive mechanisms engaged by tumor cells is induction of exhaustion phenotype in effector cells of the host immune system, such as T lymphocytes, natural killer cells, and macrophages (4). Chronic lymphocytic leukemia (CLL) is the most frequent type of leukemia recognized in western countries, accounting for about

one third of all cases of adult leukemias (5-7). The immune deficiency seen in CLL is comprehensive, leading in higher vulnerability to bacterial, viral and fungal infections, as well as deficiencies in response to tumors (8, 9). During chronic infections and cancers, which involve persistent antigen exposure, the memory T cell differentiation is markedly altered and the number of exhausted T cells is increased (10). These cells exhibit common characteristic features such as loss of effector functions, sustained upregulation and co-expression of inhibitory receptors (11, 12). Some of the immune inhibitory receptors expressed by exhausted T cells are programmed death-1 (PD-1, CD279), T cell immunoglobulin domain and mucin domain-containing protein 3 (Tim-3), cytotoxic T lymphocyte

associated protein-4 (CTLA-4), lymphocyte activation gene 3 protein (LAG-3), 2B4 (also known as CD244), and CD160 (13).

Recent studies have applied genomic approaches to investigate the transcriptional factors underlying T cell exhaustion. Both CD4+ and CD8+ exhausted T cells have a distinct transcriptional profile that is markedly different from their effector and memory counterparts, including major changes in transcription factors, the expression of inhibitory and co-stimulatory receptors, signaling molecules, cytokine and chemokine receptors, and also genes involved in metabolism (11, 14, 15). Previous studies revealed the role of B lymphocyte-induced maturation protein 1 (Blimp-1) as a transcriptional regulator of CD8+ T cell exhaustion during chronic viral infections and proposed Blimp-1 as a transcriptional regulator balancing effector function and T cell exhaustion (10, 15-17). Blimp-1 is a zinc finger-containing transcriptional repressor encoded by the *prdm-1* gene and is required for terminal differentiation of B cells into plasma cells (18-20). It has been found that Blimp-1 is induced during the later stages of CD8+ T cell activation and is required for terminal differentiation of effector CD8+ T cells (21, 22).

In our previous studies on CLL patients, we have shown that both CD4+ (23) and CD8+ T cells (24) are exhausted and show functional defects. These exhausted T cells are characterized by overexpression of Tim-3 and PD-1 immune inhibitory receptors. We have also indicated the upregulation of Gal-9 and PD-L1 immune checkpoint molecules in CLL patients as the main ligands of Tim-3 and PD-1, respectively

(25). Notwithstanding our increasing knowledge of the molecules involved in immune regulation and T cell exhaustion in CLL, the role of their related transcription factors remained unclear. In order to address this question, we surveyed the expression profile of Blimp-1 as an exhaustion transcriptional factor in CLL patients.

## Materials and Methods

### Patients and controls

Peripheral blood was collected from 25 CLL patients who had not received any chemotherapy regimens, including 13 males and 12 females with the age range of 48–84 years, attending the Hematology and Oncology Clinic of Imam Khomeini Hospital, affiliated to Mazandaran University of Medical Sciences, and 15 normal subjects, who were age- and sex-matched with CLL patients, including 9 males and 6 females with the age range of 35-77 years. A consent letter was taken from all participants and the study was approved by the Ethical Committee of Mazandaran University of Medical Sciences. CLL was diagnosed based on blood cell count, cell morphology, immunophenotyping analysis, and clinical symptoms. The patients were clinically classified according to the Rai staging system and National Cancer Institute Working Group (NCI-WG) criteria. Stages 0 and I were then defined as early clinical stage (n=16) and stages II, III and IV as advanced clinical stages (n=9). The major clinical and laboratory characteristics of our CLL patients and normal subjects are summarized in Table I.

**Table 1.** Major clinical and laboratory characteristics of CLL patients and normal controls.

Characteristics		CLL Patients (n=25)	Healthy Controls (n=15)	p-value
Sex	Male	13	9	0.24
	Female	12	4	
Age (years)	Median	62.24	58.13	0.34
	Range	48 – 84	35 -77	
WBC×10 <sup>3</sup> /mm <sup>3</sup>	Median	39.79	7.50	< 0.0001
	Range	13.48 – 112.0	4.20 – 9.79	
Lym (%)	Median	80.61	35.83	< 0.0001
	Range	56 – 95	27 – 40	
PLT×10 <sup>3</sup> /mm <sup>3</sup>	Median	173.9	214.6	0.04
	Range	38 – 365	131 – 270	
Hb (g/dl)	Median	12.19	13.47	0.04
	Range	6 – 15	11 – 15	

CLL: chronic lymphocytic leukemia, WBC: white blood cell count, Lym: lymphocytes percent in peripheral blood, PLT: platelet count, Hb: hemoglobin. P-values < 0.05 were considered significant.

*RNA extraction and cDNA synthesis*

Peripheral blood mononuclear cells (PBMCs) were isolated from all samples using Ficoll Histopaque density gradient centrifugation, according to the manufacturer's instructions (Biosera, Nuaille, France). The viability of isolated cells was > 95% as determined by trypan blue staining. Total RNA was extracted from  $8 \times 10^6$  PBMCs using RNeasy kit (CinnaGen, Tehran, Iran) based on the manufacturer's protocol. The quality of isolated RNA was confirmed by a Nano-spectrophotometer (WPA, England) and electrophoresis. Complementary DNA (cDNA) was reverse-transcribed from 1 microgram of total RNA in a 20  $\mu$ l reaction mixture containing 1  $\mu$ l random hexamer primer, 4  $\mu$ l of 5x reaction buffer, 1  $\mu$ l RNase inhibitor, 2  $\mu$ l dNTP 10mM, 200 unit RevertAid M-MuLV reverse transcriptase enzyme and appropriate RNase/DNase free water. The mixture was then incubated at 25 °C for 5 min, 42 °C for 1 hour and 70 °C for 5 min using the Thermo Scientific RevertAid first strand cDNA synthesis kit (Thermo Scientific, Massachusetts, USA).

*Quantitative Reverse-Transcriptase PCR*

The mRNA level of Blimp-1 was measured by quantitative Real Time PCR (qRT-PCR) based on 2X Thermo Scientific Maxima SYBR Green/ROX qPCR Master Mix (Thermo Scientific, Massachusetts, USA) reagent in an iCycler iQ5 Real-Time PCR system (Bio-Rad, California, USA). In addition, the mRNA level of  $\beta$ -actin, as an internal control, was measured and used to normalize the Blimp-1 gene expression. PCR was performed using the following primers: Blimp-1, forward: TAC ATA CCA AAG GGC ACA CGT, reverse: GAT TCA CAT AGC GCA TCC AGT;  $\beta$ -actin, forward: CCT TCC TGG GCA TGG AGT CCT, reverse: TGG GTG CCA GGG CAG TGA T. The PCR reactions were amplified at 95 °C for initial denaturation followed by 40 cycles at 94 °C for 30 seconds, 60 °C for Blimp-1 and 57 °C for  $\beta$ -actin for 30 seconds, and 72 °C for 30 seconds. The PCR amplicon sizes were 175 bp and 174 bp for Blimp-1 and  $\beta$ -actin, respectively. Each run was completed with a melting curve analysis to confirm the specificity of the amplification and the absence of the primer dimers. Expression levels of Blimp-1 mRNA were determined by  $2^{-\Delta C_t}$  value. The relative quantification system was used for data analysis based on the relative expression of Blimp-1 mRNA level to  $\beta$ -actin mRNA level as a housekeeping gene.

**Ethics Statement**

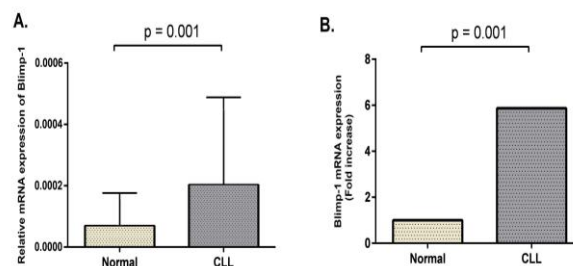
A consent letter was taken from all participants and the study was approved by the Ethical Committee of Mazandaran University of Medical Sciences.

**Statistical analysis**

Data analysis was performed using SPSS 20. Normality distribution of the obtained data was determined by Kolmogorov-Smirnov test. For comparing quantitative differences of Blimp-1 expression in patients and normal controls, the Mann-Whitney U test was used. For correlation analysis, Spearman rank correlation test was applied. Data are expressed as median (interquartile range) and p-values less than 0.05 were considered significant. All graphs were prepared using the GraphPad Prism 6 software.

**Results**

*Blimp-1 mRNA was highly expressed in CLL patients*  
Our previous findings indicated that CD4<sup>+</sup> and CD8<sup>+</sup> T cells (23, 24) from CLL patients are exhausted and show functional defects. To investigate the profile of Blimp-1 expression as an important transcription factor in T cell exhaustion, mRNA expression of Blimp-1 was measured in peripheral blood of CLL patients. The relative expression of Blimp-1 mRNA was evaluated in all samples by a qRT-PCR method using  $\beta$ -actin as an internal control. The primer efficiency was defined as 102% for Blimp-1. Our results demonstrated that Blimp-1 was highly upregulated in CLL patients compared to normal subjects ( $p = 0.001$ , Figures 1A and B). Indeed, Blimp-1 mRNA level measured in CLL patients was six times higher than that of normal controls.



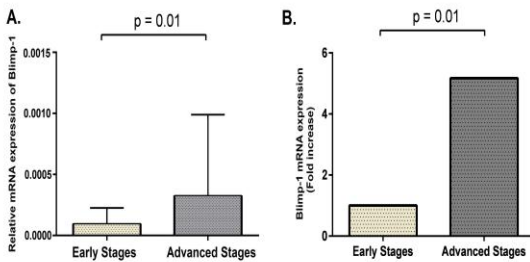
**Figure 1.** Blimp-1 mRNA expression profile in CLL patients and normal controls.

(A) Relative mRNA transcript levels of Blimp-1 from CLL patients and normal controls. (B) Fold increase of Blimp-1 in CLL patients compared to normal controls. Fold increase was calculated by dividing the mean ratio of Blimp-1 relative expression value obtained from CLL patients to normal controls. The results are represented as median  $\pm$  interquartile range of  $2^{-\Delta C_t}$  after normalization with  $\beta$ -actin as an internal control. P-values less than 0.05 were considered significant.

*Blimp-1 was more expressed in CLL patients at advanced clinical stages*

In our previous studies, we have indicated higher frequencies of exhausted CD4<sup>+</sup> and CD8<sup>+</sup> T cells in CLL patients in advanced clinical stages of the disease compared to those in early clinical stages (23, 24). Also, the frequency of exhausted CD4<sup>+</sup> and CD8<sup>+</sup> T

cells was correlated with poor prognosis of CLL patients. To confirm our previous findings, in this study, we analyzed the correlation of Blimp-1 expression with clinical stages and disease severity of the CLL patients. As shown in Figures 2A and B, our results indicated that the relative expression level of Blimp-1 was significantly higher in advanced clinical stages of CLL patients than that of early stages ( $p = 0.01$ ).

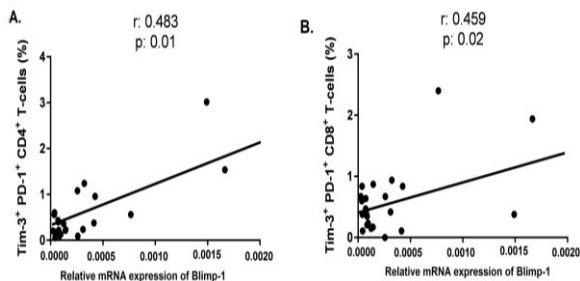


**Figure 2.** Higher expression of Blimp-1 in advanced clinical stages CLL patients.

CLL patients were clinically classified based on the Rai staging system. Stages 0 and I were defined as early clinical stage ( $n=16$ ) and stages II, III and IV as advanced clinical stages ( $n=9$ ). (A) Relative mRNA transcript levels of Blimp-1 from early and advanced clinical stages of CLL patients. (B) Fold increase of Blimp-1 in advanced clinical stages of CLL patients compared to early stages. Fold increase was calculated by dividing the mean ratio of Blimp-1 relative expression value obtained from advanced clinical stages of CLL patients to early stages. The results are represented as median  $\pm$  interquartile range of  $2^{-\Delta\Delta Ct}$  after normalization with  $\beta$ -actin as an internal control. P-values less than 0.05 were considered significant.

*Blimp-1 expression was positively correlated with the subsets of exhausted T cells from CLL patients*

To find any correlations between Blimp-1 mRNA expression and the frequency of exhausted T-CD4<sup>+</sup> and T-CD8<sup>+</sup> cells in CLL patients, the results of this study were analyzed with the frequencies of Tim-3<sup>+</sup>/PD-1<sup>+</sup>/CD4<sup>+</sup> and Tim-3<sup>+</sup>/PD-1<sup>+</sup>/CD8<sup>+</sup> T cells of CLL patients from our previous findings.



**Figure 3.** Correlation of Blimp-1 mRNA expression with the frequency of exhausted T-CD4<sup>+</sup> and T-CD8<sup>+</sup> cells in CLL patients.

Blimp-1 mRNA expression was significantly associated with the frequency of Tim-3<sup>+</sup>/PD-1<sup>+</sup>/CD4<sup>+</sup> T-cells ( $r = 0.483$ ,  $P = 0.01$ ) (A) and Tim-3<sup>+</sup>/PD-1<sup>+</sup>/CD8<sup>+</sup> T-cells of CLL patients ( $r = 0.459$ ,  $P = 0.02$ ) (B). Statistical comparisons were done by Spearman's rank correlation test.

As shown in Figure 3, the Blimp-1 mRNA expression was significantly correlated, not only with the frequency of Tim-3<sup>+</sup>/PD-1<sup>+</sup>/CD4<sup>+</sup> T cells ( $r = 0.483$ ,  $p = 0.01$ ), but also with the frequency of Tim-3<sup>+</sup>/PD-1<sup>+</sup>/CD8<sup>+</sup> T cells in CLL patients ( $r = 0.459$ ,  $p = 0.02$ ). These results suggest a potential role for Blimp-1 in the regulation of Tim-3 and PD-1 expression as an important inhibitory receptor in T cell exhaustion.

**Discussion**

T cell exhaustion is a common feature of chronic inflammatory conditions, including chronic infections and tumors, leading to poor control of the pathogens by the host immune system (26, 27). Multiple immune inhibitory pathways are involved in T cell exhaustion, and blocking these pathways can reinvigorate the immune responses during chronic complications (27-29). Although several transcription factors have been shown to regulate effector and memory T cell differentiation following acute infections, the transcriptional mechanisms of T cell exhaustion are still unclear. In our previous studies, we found out that both CD4<sup>+</sup> and CD8<sup>+</sup> T cells in patients with CLL overexpressed Tim-3 and PD-1 (23, 24). Later on, we indicated the upregulation of Gal-9 and PD-L1, main ligands of Tim-3 and PD-1, respectively, in CLL patients (25). To further explore the immune regulatory pathways in CLL, we examined the expression of Blimp-1, as a potential transcription factor regulating exhaustion processes. Our results showed a higher expression of Blimp-1 mRNA in CLL patients compared to normal individuals. Moreover, Blimp-1 mRNA was expressed higher in advanced clinical stages of CLL patients in comparison with early stages of the disease. To our knowledge, this is the first study which shows the expression of Blimp-1 in CLL.

Recent reports have demonstrated that several transcription factors regulate the immune exhaustion processes in chronic inflammatory conditions (15, 30, 31). It has been found that NFAT family of transcription factors, in the absence of AP-1 cooperation, induce a state of reduced responsiveness to subsequent stimulation both in CD4<sup>+</sup> and CD8<sup>+</sup> T cells, and this process may be a common initiating stimulus in the induction of exhaustion (31, 32). Further studies revealed the importance of T-bet and Eomes in subsets determination of terminally exhausted cells (33, 34). It has also been reported that CD8<sup>+</sup> T cells expressing TCF-1 display hallmarks of the exhausted phenotype via the expression of PD-1 and LAG-3, during chronic infections (35). Other transcription factors involved in CD4<sup>+</sup> and CD8<sup>+</sup> T cell exhaustion include Blimp-1, BATF, FoxO1, FoxO3, Zeb2, Bach2, NFIL-3, Prdm-1, Egr2, and Helios (35, 36), among which, Blimp-1 has attracted

more attention and has been introduced as an exhaustion transcription factor in various chronic pathological conditions (15, 26, 30). It has been shown that high levels of Blimp-1 is correlated with the maintenance of the exhausted cells and appeared to control the expression of PD-1 and also regulate the expression of other inhibitory receptors, including Tim-3, LAG3, CD160, and 2B4 (9, 13, 37). Consistent with these reports, conditional deletion of Blimp-1 resulted in reduced inhibitory receptor expression by exhausted T cells during chronic LCMV infection (36). Most recently, Hwang et al. reported that Blimp-1 was upregulated and acted as a critical regulator for CD4<sup>+</sup> T cell exhaustion during chronic toxoplasmosis and that conditional deletion of Blimp-1 in CD4<sup>+</sup> T cells regained CD8<sup>+</sup> T cell function and improved infection control (38). On the other hand, despite lower expression of inhibitory receptors by CD8<sup>+</sup> T cells in the absence of Blimp-1, these cells remained defective in terms of cytokine production. Therefore, it seems that other pathways may also regulate the cytokine production by the exhausted cells (10, 37, 39). These findings suggest a complex role for Blimp-1 in regulating T cell responses.

Although well studied in viral infections, few studies addressed the regulatory role of Blimp-1 in immune response to tumors, such as leukemias (40). Zhu et al. demonstrated more expression of Blimp-1 in both CD4<sup>+</sup> and CD8<sup>+</sup> T cells of AML patients, and that Blimp-1<sup>+</sup> T cells express high levels of co-inhibitory receptors, such as PD-1 and TIGIT (40). The mechanisms by which Blimp-1 regulates T cell responses are not fully understood. We found a correlation between Blimp-1 expression and co-expression of inhibitory receptors, Tim-3 and PD-1, on both CD4<sup>+</sup> and CD8<sup>+</sup> T cells. Some other studies have demonstrated the potential roles of Tim-3 and PD-1 in inhibition of anti-leukemia T cell responses (9, 24, 41). We assume that in CLL, Blimp-1 suppresses T cell function through the positive regulation of Tim-3/Gal-9 and PD-1/PD-L1 pathways and facilitates evasion of tumor cells from immune effector mechanisms. Therefore, these findings demonstrated that Blimp-1 is a transcriptional regulator of immune inhibitory receptors.

To our knowledge, this is the first study indicating Blimp-1 overexpression in CLL and its association with T cell exhaustion. Although other transcription factors and pathways contributing to T cell exhaustion remained to be understood, this study introduces Blimp-1 as a potential transcription regulator of T cell exhaustion in CLL. This leads to a better understanding of underlying mechanisms of T cell exhaustion which could be helpful in finding new therapeutic strategies for CLL.

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## Conflict of Interest

The authors declare that the current research was conducted in the absence of any commercial or financial relationships that could be considered as conflict of interest.

## References

1. Diefenbach A, Raulet DH. The innate immune response to tumors and its role in the induction of T-cell immunity. *Immunol Rev.* 2002; 188(1):9-21. PMID: 12445277
2. Zitvogel L, Tesniere A, Kroemer G. Cancer despite immunosurveillance: immunoselection and immunosubversion. *Nat Rev Immunol.* 2006; 6(10):715. PMID: 16977338
3. Swann JB, Smyth MJ. Immune surveillance of tumors. *J Clin Invest.* 2007; 117(5):1137. PMID: 17476343
4. Patil S, Rao RS, Majumdar B. T-cell Exhaustion and Cancer Immunotherapy. *Journal of international oral health: JIOH.* 2015; 7(8):i-ii. PMID: 26464560
5. Hallek M. Chronic lymphocytic leukemia: 2015 update on diagnosis, risk stratification, and treatment. *Am J Hematol.* 2015; 90(5):446-60. PMID: 25908509
6. Hallek M, Pflug N. Chronic lymphocytic leukemia. *Ann Oncol.* 2010; 21(suppl 7): vii154-64. PMID: 20943609
7. Herishanu Y, Polliack A. Chronic lymphocytic leukemia: a review of some new aspects of the biology, factors influencing prognosis and therapeutic options. *Transfus Apher Sci.* 2005; 32(1):85-97. PMID: 15737877
8. Catovsky D, Miliani E, Okos A, Galton D. Clinical significance of T-cells in chronic lymphocytic leukaemia. *Lancet.* 1974; 304(7883):751-2. PMID: 4143015
9. Riches JC, Davies JK, McClanahan F, Fatah R, Iqbal S, Agrawal S, et al. T cells from CLL patients exhibit features of T-cell exhaustion but retain capacity for cytokine production. *Blood.* 2013; 121(9):1612-21. PMID: 23247726
10. Wherry EJ. T cell exhaustion. *Nat Immunol.* 2011; 12(6):492-9. PMID: 21739672
11. Doering TA, Crawford A, Angelosanto JM, Paley MA, Ziegler CG, Wherry EJ. Network analysis reveals centrally connected genes and pathways involved in CD8<sup>+</sup> T cell exhaustion versus memory. *Immunity.* 2012; 37(6):1130-44. PMID: 23159438
12. Schietinger A, Greenberg PD. Tolerance and exhaustion: defining mechanisms of T cell dysfunction. *Trends Immunol.* 2014; 35(2):51-60. PMID: 24210163
13. Blackburn SD, Shin H, Haining WN, Zou T, Workman CJ, Polley A, et al. Coregulation of CD8<sup>+</sup> T cell exhaustion by multiple inhibitory receptors during chronic viral infection. *Nat Immunol.* 2009; 10(1):29-37. PMID: 19043418
14. Crawford A, Angelosanto JM, Kao C, Doering TA, Odorizzi PM, Barnett BE, et al. Molecular and transcriptional basis of CD4<sup>+</sup>

- T cell dysfunction during chronic infection. *Immunity*. 2014; 40(2):289-302. PMID: 24530057
15. Wherry EJ, Ha S-J, Kaech SM, Haining WN, Sarkar S, Kalia V, et al. Molecular signature of CD8+ T cell exhaustion during chronic viral infection. *Immunity*. 2007; 27(4):670-84. PMID: 17950003
16. Yi JS, Cox MA, Zajac AJ. T-cell exhaustion: characteristics, causes and conversion. *Immunology*. 2010; 129(4):474-81. PMID: 20201977
17. Day CL, Kaufmann DE, Kiepiela P, Brown JA, Moodley ES, Reddy S, et al. PD-1 expression on HIV-specific T cells is associated with T-cell exhaustion and disease progression. *Nature*. 2006; 443(7109):350-4. PMID: 16921384
18. Turner CA, Mack DH, Davis MM. Blimp-1, a novel zinc finger-containing protein that can drive the maturation of B lymphocytes into immunoglobulin-secreting cells. *Cell*. 1994; 77(2):297-306. PMID: 8168136
19. Shaffer A, Lin K-I, Kuo TC, Yu X, Hurt EM, Rosenwald A, et al. Blimp-1 orchestrates plasma cell differentiation by extinguishing the mature B cell gene expression program. *Immunity*. 2002; 17(1):51-62. PMID: 12150891
20. Shapiro-Shelef M, Lin K-I, McHeyzer-Williams LJ, Liao J, McHeyzer-Williams MG, Calame K. Blimp-1 is required for the formation of immunoglobulin secreting plasma cells and pre-plasma memory B cells. *Immunity*. 2003; 19(4):607-20. PMID: 14563324
21. Kallies A, Xin A, Belz GT, Nutt SL. Blimp-1 transcription factor is required for the differentiation of effector CD8+ T cells and memory responses. *Immunity*. 2009; 31(2):283-95. PMID: 19664942
22. Rutishauser RL, Martins GA, Kalachikov S, Chandele A, Parish IA, Meffre E, et al. Transcriptional repressor Blimp-1 promotes CD8+ T cell terminal differentiation and represses the acquisition of central memory T cell properties. *Immunity*. 2009; 31(2):296-308. PMID: 19664941
23. Taghiloo S, Allahmoradi E, Tehrani M, Hossein-Nataj H, Shekarriz R, Janbabaie G, et al. Frequency and functional characterization of exhausted CD8+ T cells in chronic lymphocytic leukemia. *Eur J Haematol*. 2017; 98(6):622-31. PMID: 28306177.
24. Taghiloo S, Allahmoradi E, Ebadi R, Tehrani M, Hosseini-Khah Z, Janbabaie G, et al. Upregulation of Galectin-9 and PD-L1 Immune Checkpoints Molecules in Patients with Chronic Lymphocytic Leukemia. *Asian Pac J Cancer Prev*. 2017; 18(8):2269-74. PMID: 28843266
25. Shin H, Wherry EJ. CD8 T cell dysfunction during chronic viral infection. *Curr Opin Immunol*. 2007; 19(4):408-15. PMID: 17656078
26. Sakuishi K, Apetoh L, Sullivan JM, Blazar BR, Kuchroo VK, Anderson AC. Targeting Tim-3 and PD-1 pathways to reverse T cell exhaustion and restore anti-tumor immunity. *J Exp Med*. 2010; 207(10):2187-94. PMID: 20819927
27. Freeman GJ, Wherry EJ, Ahmed R, Sharpe AH. Reinvigorating exhausted HIV-specific T cells via PD-1–PD-1 ligand blockade. *J Exp Med*. 2006; 203(10):2223-7. PMID: 17000870
28. Sharpe AH, Wherry EJ, Ahmed R, Freeman GJ. The function of programmed cell death 1 and its ligands in regulating autoimmunity and infection. *Nat Immunol*. 2007; 8(3):239-45. PMID: 17304234
29. Wherry EJ, Kurachi M. Molecular and cellular insights into T cell exhaustion. *Nat Rev Immunol*. 2015; 15(8):486. PMID: 26205583
30. Mogno GP, Spreafico R, Wong V, Scott-Browne JP, Togher S, Hoffmann A, et al. Exhaustion-associated regulatory regions in CD8+ tumor-infiltrating T cells. *Proc Natl Acad Sci U S A*. 2017; 114(13):E2776-E85. PMID: 28283662
31. Martinez GJ, Pereira RM, Aijö T, Kim EY, Marangoni F, Pipkin ME, et al. The transcription factor NFAT promotes exhaustion of activated CD8+ T cells. *Immunity*. 2015; 42(2):265-78. PMID: 25680272
32. Blackburn SD, Shin H, Freeman GJ, Wherry EJ. Selective expansion of a subset of exhausted CD8 T cells by  $\alpha$ PD-L1 blockade. *Proc Natl Acad Sci U S A*. 2008; 105(39):15016-21. PMID: 18809920
33. Paley MA, Kroy DC, Odorizzi PM, Johnnidis JB, Dolfi DV, Barnett BE, et al. Progenitor and terminal subsets of CD8+ T cells cooperate to contain chronic viral infection. *Science*. 2012; 338(6111):1220-5. PMID: 23197535
34. Pereira RM, Hogan PG, Rao A, Martinez GJ. Transcriptional and epigenetic regulation of T cell hyporesponsiveness. *J Leukoc Biol*. 2017; 102(3):601-615. PMID: 28606939
35. Shin H, Blackburn SD, Intlekofer AM, Kao C, Angelosanto JM, Reiner SL, et al. A role for the transcriptional repressor Blimp-1 in CD8+ T cell exhaustion during chronic viral infection. *Immunity*. 2009; 31(2):309-20. PMID: 19664943
36. Lu P, Youngblood BA, Austin JW, Mohammed AUR, Butler R, Ahmed R, et al. Blimp-1 represses CD8 T cell expression of PD-1 using a feed-forward transcriptional circuit during acute viral infection. *Journal Exp Med*. 2014; 211(3):515-27. PMID: 24590765
37. Hwang S, Cobb DA, Bhadra R, Youngblood B, Khan IA. Blimp-1-mediated CD4 T cell exhaustion causes CD8 T cell dysfunction during chronic toxoplasmosis. *J Exp Med*. 2016; 213(9):1799-818. PMID: 27481131
38. Angelosanto JM, Wherry EJ. Transcription factor regulation of CD8+ T-cell memory and exhaustion. *Immunol Rev*. 2010; 236(1):167-75. PMID: 20636816
39. Zhu L, Kong Y, Zhang J, Claxton DF, Ehmann WC, Rybka WB, et al. Blimp-1 impairs T cell function via upregulation of TIGIT and PD-1 in patients with acute myeloid leukemia. *J Hematol Oncol*. 2017; 10(1):124. PMID: 28629373
40. Zhou Q, Munger ME, Veenstra RG, Weigel BJ, Hirashima M, Munn DH, et al. Coexpression of Tim-3 and PD-1 identifies a CD8+ T-cell exhaustion phenotype in mice with disseminated acute myelogenous leukemia. *Blood*. 2011; 117(17):4501-10. PMID: 21385853