Recent insights in the pathogenesis of post-transplantation lymphoproliferative disorders

Julie Morscio, Thomas Tousseyn

Julie Morscio, Department for Imaging and Pathology, Translational Cell and Tissue Research, 3000 Leuven, Belgium

Thomas Tousseyn, Department of Pathology, University Hospitals Leuven, 3000 Leuven, Belgium

Author contributions: Morscio J wrote the paper; Tousseyn T revised the paper.

Conflict-of-interest statement: No potential conflicts of interest.

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Manuscript source: Invited manuscript

Correspondence to: Thomas Tousseyn, MD, PhD, Department of Pathology, University Hospitals Leuven, Herestraat 49, 3000 Leuven, Belgium. thomas.tousseyn@uzleuven.be
Telephone: +32-16-336582
Fax: +32-16-336622

Received: April 23, 2016
Peer-review started: April 24, 2016
First decision: June 6, 2016
Revised: July 8, 2016
Accepted: August 17, 2016
Article in press: August 18, 2016
Published online: September 24, 2016

Abstract

Post-transplant lymphoproliferative disorder (PTLD) is an aggressive complication of solid organ and hematopoietic stem cell transplantation that arises in up to 20% of transplant recipients. Infection or reactivation of the Epstein-Barr virus (EBV), a ubiquitous human herpesvirus, in combination with chronic immunosuppression are considered as the main predisposing factors, however insight in PTLD biology is fragmentary. The study of PTLD is complicated by its morphological heterogeneity and the lack of prospective trials, which also impede treatment optimization. Furthermore, the broad spectrum of underlying disorders and the graft type represent important confounding factors. PTLD encompasses different malignant subtypes that resemble histologically similar lymphomas in the general population. Post-transplant diffuse large B-cell lymphoma (PT-DLBCL), Burkitt lymphoma (PT-BL) and plasmablastic lymphoma (PT-PBL) occur most frequently. However, in many studies various EBV+ and EBV- PTLD subtypes are pooled, complicating the interpretation of the results. In this review, studies of the gene expression pattern, the microenvironment and the genetic profile of PT-DLBCL, PT-BL and PT-PBL are summarized to better understand the mechanisms underlying post-transplantation lymphomagenesis. Based on the available findings we propose stratification of PTLD according to the histological subtype and the EBV status to facilitate the interpretation of future studies and the establishment of clinical trials.

Key words: Epstein-Barr virus; Post-transplant lymphoproliferative disorder; Immunodeficiency; Diffuse large B-cell lymphoma; Burkitt lymphoma; Plasmablastic lymphoma

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Core tip: At the moment different post-transplant lymphoproliferative disorders (PTLD) are grouped in broad categories (early, polymorphic, monomorphic and Hodgkin-like PTLD) and the Epstein-Barr virus (EBV) status is not taken into account. However, increasing
INTRODUCTION

Despite the increasing incidence of cancer worldwide, only a limited number of cancer-causing factors have been identified. Viruses are amongst them: An estimated 15% of cancers are attributed to viral infections. One of the most widely spread oncogenic viruses is the Epstein-Barr virus (EBV), a gamma human herpesvirus with a seroprevalence of 90%-95% in adults. EBV, discovered in 1964[1], is best known as the cause of infectious mononucleosis (or kissing disease)[2]. EBV-driven lymphoproliferative disorders (LPD) are characterized by an EBV-driven immortalization of B-cells. In an otherwise healthy individual, development of such LPD is countered by a strong immune response [mainly of cytotoxic T-cells (CTL)], which ultimately resolves the infection. However, when the immune system is compromised [e.g., in acquired immunodeficiency syndrome (AIDS) patients or in organ transplant recipients under chronic immunosuppression] EBV-driven LPD may eventually progress to overt lymphoma.

During the last decades, the number of solid organ (e.g., kidney, heart, liver, etc.) and stem cell transplantations has increased significantly. In parallel, the risk of graft rejection has dropped thanks to the development of more potent immunosuppressive agents resulting in longer survival of transplant recipients. However, a major drawback of the chronically immunosuppressed status of these individuals is the development of a potentially fatal post-transplant lymphoproliferative disorder (PTLD) in up to 20% of transplant recipients[3]. PTLD is a relatively new disease entity that is now widely recognized. The first cases were described in renal transplant patients, shortly after the introduction of chronic immunosuppressive drugs in the 1960s[4]. Despite the strong association between EBV and PTLD (about 70% of PTLD are EBV-positive, EBV+), disease biology is not well understood[3]. The pathological presentation of PTLD is variable, ranging from a localized benign LPD to lymphoma associated with poor survival[5]. Treatment of PTLD patients is largely based on insights in lymphomagenesis in immunocompetent patients, in which there is no evident role for EBV in the majority of cases. For application of more adequate therapy it is indispensable to characterize PTLD more thoroughly.

The most common malignant PTLD subtype is post-transplant diffuse large B-cell lymphoma (PT-DLBCL), followed by Burkitt lymphoma (PT-BL) and plasmablastic lymphoma (PT-PBL). PT-BL and PT-PBL are aggressive, but poorly studied malignant PTLD subtypes. The number of reported cases is limited and most studies mainly focus on patient management[6-9].

In this review we summarize the available data on the genetic profile, the gene expression pattern and the microenvironment of these malignancies to better understand the mechanisms underlying post-transplantation lymphomagenesis. A literature search was performed for “PTLD” or “post-transplant lymphoproliferative disorder” with or without ”diffuse large B-cell lymphoma”, ”Burkitt lymphoma” or ”plasmablastic lymphoma” and the available literature regarding PTLD pathogenesis was collected. For a review of the diagnosis and management of PTLD we refer the reader to[3,10].

DISCUSSION

EBV exploits the germinal center route of B-cell activation

During a normal humoral immune response, a circulating B-cell that encounters its cognate antigen becomes an activated blast with two possible fates. The B-cell can mature into a short-lived plasma cell that quickly produces IgM class antibodies with limited specificity (T-cell independent pathway). Alternatively, the B-cell may form a germinal center (GC) in a lymph node, mucosa-associated lymphoid tissue or spleen (T-cell dependent pathway). In the GC, the specificity of the B-cell’s antibody is enhanced by somatic hypermutation (SHM, random mutation of the antibody’s variable chain, IgV) and its functional versatility is altered by class switch recombination from IgM to IgG, IgE or IgA. Eventually, the B-cell matures into a plasma cell or a memory B-cell[11]. B-cells transiting the GC are germinal center B-cells (GCB). B-cells that have completed the GC reaction are called activated B-cells, non-GCB or post-germinal B-cells (Figure 1).

According to the classic model, EBV infects naive B-cells and promotes formation of a GC. During GC transition, EBV proteins provide a selective advantage and stimulate differentiation to memory B-cells, the presumed reservoir of EBV. This process is enabled by coordinate expression of EBV proteins, primarily latent membrane proteins (LMP1, 2A-B) and EBV nuclear antigens (EBNA1, 2, 3A-C). Based on the pattern of expression, three different latency expression profiles are recognized[12]. These latency programs are associated with different stages of EBV B-cell infection and with particular lymphoproliferative disorders (Table 1 and...
Figure 1: The Epstein-Barr virus exploits normal B-cell activation pathways. Activation of a naïve B-cell (that expresses IgM and IgD on its surface) by its cognate antigen results in B-cell activation and differentiation into a memory B-cell or a plasma cell, most commonly via T-cell dependent activation. The antigen-activated B-cell enters a primary follicle in lymph node or spleen and forms a germinal center (GC), transforming the primary follicle into a secondary follicle. This structure is composed of three distinct regions. The marginal zone,[1] which consists mainly of activated B-cells and GC-matured IgM+ B-cells, the mantle zone or corona[2], which comprises naïve and memory B-cells surrounds the GC.[3] The GC consists of a dark zone and a light zone. In the dark zone, the activated B-cells (centroblasts) proliferate and downregulate expression of IgM and IgD to allow somatic hypermutation (SHM) and class switch recombination (CSR), increasing the antibody’s affinity, specificity and functional versatility. In the light zone of the GC, the B-cells (centrocytes) with the best antibody are selected and ultimately mature into memory B-cells or plasma cells. Instead of IgM and IgD, these express high affinity IgG, IgA or IgE antibodies. Classically, Epstein-Barr virus (EBV) infects naïve B-cells that are stimulated to form a GC. In the activated blast, viral latency III (LMP1+/EBNA2+) is expressed and induces proliferation. In the GC, latency II (LMP1+/EBNA2-) is expressed and infected centroblasts presumably undergo SHM and CSR, involved in antibody maturation. After leaving the GC, they differentiate into plasma cells or (mainly) memory cells (latency I, EBNA1+ or latency 0, no expression of viral proteins). In vitro and in vivo, plasma cell differentiation results in activation of the EBV lytic cycle. In all stages, the viral DNA (circle in the nucleus) is maintained as an episome. Images from www.somersault1824.com were used in this figure. PBL: Plasmablastic lymphoma; DLBCL: Diffuse large B-cell lymphoma; ABC: Activated B-cell; GCB: Germinal center B-cell.

Table 1: Epstein-Barr virus-driven lymphoproliferative disorders are linked with particular Epstein-Barr virus latency programs

| Latency | Expressed EBV gene products | Normal B-cell stage | Associated disease |
|---------|---------------------------|---------------------|-------------------|
| III     | EBER1-2, EBNA1-6, LMP1, LMP2A-B | Activated B lymphoblast | PT-DLBCL, AIDS-related lymphoma, Acute infectious mononucleosis |
| II      | EBER 1-2, EBNA1, LMP1-2A | B-cell undergoing the GC reaction | PT-DLBCL, Classical Hodgkin lymphoma |
| I       | EBER 1-2, EBNA1 | Memory B-cell (PT-+) | Burkitt lymphoma (PT-) PBL |

EBER: Epstein-Barr virus-encoded RNA; EBNA: Epstein-Barr virus nuclear antigen; LMP: Latent membrane protein; PT-DLBCL: Post-transplant diffuse large B-cell lymphoma; PBL: Plasmablastic lymphoma; EBV: Epstein-Barr virus.

Figure 1). EBV+ PT-DLBCL is classically associated with the most elaborate virus expression pattern, latency III. EBV+ PT-BL and PT-PBL on the other hand most frequently express the more restricted latency patterns I or II[13,14].

LMP1, a constitutively active mimic of CD40 (a crucial costimulatory factor in T-cell mediated B-cell activation), is regarded as the major oncogenic protein of EBV. LMP2A is a functional mimic of a B-cell receptor and provides survival signals to the B-cells. EBNA1 ensures replication of the viral genome during cell division. EBNA2 acts as a master transcriptional regulator of both viral and cellular genes[12]. Two viral miRNA clusters (BART-miRNAs and BHRF1 miRNAs) are differentially expressed depending on the particular viral latency program[15]. EBV-encoded RNA (EBER) 1 and 2 are the only gene products that are expressed throughout all latency and lytic phases of the viral cycle and represent the most reliable markers to determine EBV infection[16].

Key features of EBV latent proteins are shown in Figure 2A. For more details about the viral gene products we refer the reader to other reviews[17,18].

In vitro and in vivo, plasma cell differentiation of an EBV-infected B-cell is associated with activation of EBV lytic replication resulting in production of new viral
Figure 2 Common and distinct pathogenetic mechanisms in Epstein-Barr virus-positive and -negative post-transplant diffuse large B-cell lymphoma. A: Two Epstein-Barr virus (EBV) proteins that are thought to play a role in EBV-driven lymphomagenesis are LMP1 and LMP2A. LMP1 is analogous to CD40 and promotes cell transformation by inducing NF-κB, that in turn upregulates BCL-2, A20 and C-FLIP, all involved in blocking apoptosis. LMP2A mimics a chronically active B-cell receptor (BCR) and prevents BCR-mediated activation of EBV lytic replication. LMP2A also provides the necessary survival signals which can compensate for the loss of a functional BCR. Other pathways that are induced comprise janus kinase, p38-MAPK and PI3K signaling. Nuclear EBNA1 and EBNA2 are involved in replication of the viral episome and induction of viral as well as cellular genes respectively; B: The pathogenesis of EBV-positive and -negative lymphoma is marked by a number of common as well as distinct pathogenetic mechanisms. Mechanisms that contribute to both EBV-positive and -negative lymphoma involve iatrogenic T-cell suppression, microsatellite instability (resulting in accumulation of mutations), epigenetic alterations (mainly hypometylation), host polymorphisms (in particular in genes encoding proteins involved in immunity), aberrant somatic hypermutation (SHM, resulting in accumulation of point mutations) and aberrant up- or down-regulation of host miRNAs which may substantially impact gene expression. EBV-negative PT-DLBCL is characterized by genetic aberrations found in EBV-positive DLBCL arising in the general population, e.g., alterations involving FOXP1. EBV-positive PT-DLBCL on the other hand harbors fewer genetic lesions. Gain of 9p24.1 (harboring PDL1/2, JAK2) has been detected and may contribute to tumor immune evasion. A minority of the EBV-positive cells actively produce viral particles. This lytic replication may promote lymphoma growth by expression of IL-6 and VEGF. Also viral IL-10 (vIL10) is expressed which contributes to suppression of anti-tumor responses by antagonizing IFN-γ. The expression of EBV proteins attracts cytotoxic T-cells (CTLs) to the site of the tumor however the question remains whether effective anti-tumor responses can be produced as also tolerant immune responses are induced. IDO1 (expressed in tumor cells and dendritic cells) and PDL1 (expressed in tumor cells and macrophages) suppress T-cells and may substantially impair the activity of CTLs. Also CD163+ macrophages (thought to be immunotolerant M2 macrophages) may play a role in immune evasion. Images from www.somersault1924.com were used in this figure. PT-DLBCL: Post-transplant diffuse large B-cell lymphoma; IL: Interleukin; IFN: Interferon; VEGF: Vascular endothelial growth factor; BCR: B-cell Receptor.
consistently EBV+ and arise early after transplantation. They may derive from naïve pre-GC B-cells or from B-cells that have transited the GC without completing the GC program[34-36].

Genetics: Genetic studies have demonstrated that PT-DLBCL has genomic aberrations in common with DLBCL arising in immunocompetent individuals (gains of 8q24 harboring MYC, 3q27 harboring BCL6, 18q21 harboring BCL2, 7q harboring CDK6; loss of 17p13 harboring TP53) but also bears distinct alterations (gain of 5p, loss of 4q, 17q, Xp)[37,38]. EBV+ and EBV PTLD are rarely distinguished, but in one study EBV PT-DLBCL was associated with gains of 7p, 7q and 11q24-q25 and del(4q25-q35)[39]. EBV+ PT-DLBCL on the other hand frequently harbored trisomies of chromosomes 9 and 11. It has been suggested that overall, EBV+ PT-DLBCL carries fewer (recurrent) genetic lesions than EBV- cases[37].

An aCGH study on a series of 21 non-GCB PT-DLBCL validated these findings[40]. Overall, EBV+ PT-DLBCL harbored fewer copy number alterations than EBV cases. EBV+ and EBV PT-DLBCL shared only one recurrent aberration (gain 12q21q22); the significance of this lesion is unclear. The most frequent genetic aberration detected in the EBV+ cases was gain of 9p24.1 that harbors PD1, PD2 and JAK2 and could contribute to PD1 overexpression (Figure 2B). Notably, also in EBV- DLBCL in elderly individuals (DLBCL-E) gain of 9p24.1 was among the most frequently detected lesions[41] suggesting that overlapping processes underlie the pathogenesis of EBV-driven lymphomas.

In contrast, EBV- PT- and IC-DLBCL shared many common aberrations (gain of chromosome 3/3q and 18q, and loss of 6q23.3/TNFAIP3 and 9p21/CDKN2A) characteristic for non-GCB DLBCL[42] suggesting EBV- PT-DLBCL and IC-DLBCL are biologically similar (Figure 2B).

SHM may also contribute to oncogenesis when it misfires and results in mutation of proto-oncogenes, like PIM1, PAX5, Rhoh/TTF and MYC. Because primarily the 5′ regulatory region is targeted, aberrant SHM may alter the expression profile of the affected gene(s)[20]. In one study, aberrant SHM of PIM1, PAX5, Rhoh/TTF and/or MYC was detected in 40% of PT-DLBCL, independently of the EBV status[29,43].

Microsatellite instability (MSI) is induced by loss of a gene involved in DNA mismatch repair accelerating the accumulation of mutations (mainly in microsatellite sequences). Interestingly, MSI seems restricted to immunodeficiency-related lymphomas and has been reported in a fraction of PTLD, unrelated to EBV status (in a series of 72 PT-DLBCL, 7% was microsatellite stable tumors[44,45]). In colon carcinoma, MSI has been associated with an increased number of tumor-infiltrating lymphocytes (presumably because of the formation of neo-antigens which are then presented in MHC I on the surface of the tumor cell) suggesting that MSI lymphomas are more immunogenic than microsatellite stable tumors[45,46]. It is feasible that such immunogenic lymphomas are only tolerated in an immunocompromised host, accounting for the lack of MSI lymphomas in immunocompetent individuals.

Gene expression profile: Two early gene expression profiling studies of PTLD produced partly contradictory results, probably because of the small sample size and the different composition of the case series. Segregation of eight PT-DLBCL cases based on the EBV status in a study by Craig et al[32] could not be confirmed by a report of Vakiani et al[30], who suggested that PTLD was distinct from non-Hodgkin lymphoma in immunocompetent individuals. As a result, a number of key questions remained unresolved until recently. Are EBV+ and EBV PTLD different or not? And how do these disease states relate to lymphoma in the general population?

Consistent with the study of Craig et al[32] a GEP study of 21 PT-DLBCL by our group pointed to a dominant role for cytotoxic antiviral immune signaling in EBV+ vs EBV cases, implying that the presence of EBV in the tumor cells greatly affects the microenvironment[47].

Cytokines upregulated in EBV+ PT-DLBCL and associated with viral infection included CCL3, CCL4 and CCL8 involved in chemotaxis and/or activation of monocytes (CCL3, CCL4) and T-cells (CCL3, CCL8). Notably, CCL3 and CCL4 could also be part of an autocrine loop: In vitro, these cytokines were highly expressed by EBV+ lymphoblastoid cell lines (LCL) and promoted LCL proliferation and survival[48].

In contrast to Craig et al[32] we also detected enhanced immunotolerant signaling (PD1, IDO1) in EBV+ vs EBV PT-DLBCL (Figure 2B). These networks are likely induced to counter pro-inflammatory signaling. Upregulation of PD1 is in line with in vitro studies that demonstrated a functional link between EBV and PD1 expression in tumor cells[49], confirmed by histological studies of human EBV+ tumor biopsies[50]. IDO1 is involved in suppression of T-cells by degradation of tryptophan and was previously found overexpressed in EBV+ gastric carcinoma[51].

Notably, blockade of immune checkpoints (IDO1 or the PD1-PD1 axis) results in boosting of the immune response and has already shown promising results in clinical cancer trials[52]. This approach may be useful also in PTLD where it may increase the efficacy of adoptive T-cell therapy. However, because of the associated increased risk of graft rejection, the safety of checkpoint inhibitors in PTLD treatment requires further investigation.

EBV+ PT-DLBCL represents the minority of PT-DLBCL cases, however there is some evidence that its incidence is increasing[53], potentially (partly) because of the overall longer survival of transplant recipients. The etiology of EBV PTLD is unknown and therefore a major
question is how these tumors relate to EBV lymphomas in the general population.

A number of hypotheses have been raised to explain the etiology of EBV PTLD.

The hit-and-run theory, based on in vitro data\textsuperscript{54}, states that after transformation EBV-infected B-cells may eventually lose (part of) the viral genome. However so far, there is no in vivo evidence supporting this theory\textsuperscript{55,56}.

Given the strong association between EBV and PTLD other infectious agents, e.g., HHV8 or cytomegalovirus (CMV) may be implicated in EBV\textsuperscript{+} PTLD. However, PTLD cases in which HHV8 is detected are extremely rare\textsuperscript{57,58} and because CMV does not infect B-cells it can only play an indirect role\textsuperscript{59}. A study of AIDS-related lymphoma found only EBV to be significantly associated with pathogenesis, suggesting that also EBV PTLD is probably not caused by an infectious agent\textsuperscript{60}.

Craig et al\textsuperscript{32} suggested that EBV\textsuperscript{+} and EBV\textsuperscript{-} monomorphic PTLD are biologically distinct and the results of our GEP analysis support this hypothesis. In the comparison of GEP data of EBV\textsuperscript{+} and EBV\textsuperscript{-} DLBCL, BCR signaling was upregulated in EBV\textsuperscript{+} cases. As suggested by the authors, this finding could be the result of mimicked BCR signaling by LMP2A in EBV\textsuperscript{+} PT-DLBCL\textsuperscript{32}, however it could also be an artifact: Because of dominant immune signaling in EBV\textsuperscript{+} cases tumoral BCR signaling is seemingly upregulated in EBV cases.

To gain more insight in the biology of EBV\textsuperscript{+} PT-DLBCL, GEP profiles of EBV PT and IC cases were compared. Only pathways involved in T-cell signaling were significantly differentially expressed and downregulated in PT compared to IC-DLBCL suggesting that the tumoral expression profiles are overall similar. Notably, decreased T-cell signaling explains why some cases of EBV PT-DLBCL respond to RIS\textsuperscript{61,62}, which is generally more effective for EBV\textsuperscript{+} lesions. Therefore, restoration of the immune response in EBV PTLD patients should remain one of the cornerstones of treatment.

Notably, gain of chromosome 3/3q (encoding FOXP1) in EBV IC/PT-DLBCL had the strongest impact on gene expression (Figure 2B). Bio-informatics analysis of the gene set upregulated in this subgroup predicted that FOXP1, a master transcriptional regulator, regulates the expression of the majority of the genes (unreported data), suggesting FOXP1 is a major network hub in the pathogenesis of these cases. Because several studies support a central role of FOXP1 in non-GCB DLBCL pathogenesis\textsuperscript{53} the downregulation of FOXP1 in EBV\textsuperscript{+} non-GCB PT-DLBCL is striking. Also following in vitro EBV infection of peripheral blood mononuclear cells FOXP1 is downregulated\textsuperscript{60}, indicating that FOXP1 expression is incompatible with EBV signaling. An interesting question is whether forced expression of FOXP1 in EBV\textsuperscript{+} non-GCB DLBCL cells is toxic for the tumor cells.

Microenvironment: The tumor microenvironment consists of the collection of stromal and immune cells that make up the cellular environment in which the tumor cells reside and has been shown to significantly influence prognosis in different lymphoma subtypes\textsuperscript{65,66} also in PTLD. Particularly the infiltration of CTL has been associated with favorable prognosis (the EBV status was not taken into account). In the same study, the infiltration of regulatory T-cells (Treg), immune response modulators that prevent excessive immune activation, was limited in all PTLD cases\textsuperscript{67}. This may be attributed to obstruction of Treg cell development by immunosuppressive agents. Analysis of the normal intestinal mucosa showed that liver transplant patients on a long-term combination regimen had significantly lower levels of Treg cells compared to healthy controls\textsuperscript{68}. Although the scarcity of Treg cells in PTLD lesions may impede suppression of anti-tumor immune responses, also inhibition of B-cell proliferation by Treg cells is alleviated, potentially contributing to PTLD development\textsuperscript{69}. A thorough review of the microenvironment of PTLD has not been performed but a study of AIDS-related DLBCL may give clues: Increased tumor vascularization and a higher number of infiltrating CTL were detected in EBV\textsuperscript{+} compared to EBV\textsuperscript{-} cases\textsuperscript{69}.

Cell counts for different immune markers (manuscript submitted) performed on a series of PT-DLBCL showed increased infiltration of CD8\textsuperscript{+} CTL in part of the EBV\textsuperscript{+} compared to EBV\textsuperscript{-} cases. CTL, probably attracted to the tumor site by the presence of EBV, expressed granzyme B suggesting they were activated (Figure 2B). In contrast, NK cells, critical cytotoxic effector cells in the early response to viral infection and tumor cells, were virtually absent in all biopsies, based on staining for NCAM1/CD56. However, this does not exclude a role for NK cells in PTLD. In a study involving pediatric transplant recipients, CD56\textsuperscript{dim} NK cells were abundant only in asymptomatic transplant recipients whereas in PTLD patients, the functionally impaired CD56\textsuperscript{dim/negative} NK population was increased\textsuperscript{70}.

Tumor immune evasion is a major challenge for effective cancer treatment\textsuperscript{71} and several reports have shown that such mechanisms also play a role in PTLD. Tumoral expression of PDL1, involved in T-cell suppression\textsuperscript{72}, as well as galectin-1, involved in apoptosis-induction of CTL among others\textsuperscript{73} has been reported\textsuperscript{51}. Also immunoregulatory M2 macrophages (marked by CD163 expression) may be part of a negative feedback loop to prevent excessive CTL-induced tissue damage\textsuperscript{74}. M2 macrophages, which were significantly more abundant in EBV\textsuperscript{+} vs EBV\textsuperscript{-} PT-DLBCL (manuscript submitted), are thought to contribute to tissue remodeling and tumor progression in contrast to classical pro-inflammatory M1 macrophages\textsuperscript{75} (Figure 2B). These data are consistent with studies of EBV\textsuperscript{-} DLBCL-E and EBV\textsuperscript{-} Hodgkin lymphoma. Also in these malignancies, the presence of EBV has been associated with upregulation of CD163 expression\textsuperscript{71,74}.

It is not clear whether these cells are recruited to the
tumor site or develop in situ. Studies have shown that the M2 phenotype can be induced by particular cytokines, among which IL-4 and IL-10[80]. We speculate that also EBV-encoded IL-10 contributes to M2 macrophage polarization in EBV+ PT-DLBCL[75]. Interestingly, M2 macrophages are themselves producers of IL-10 and may be the source of the high levels of IL-10 detected in PTLD patients[77].

In a prospective trial of Hodgkin lymphoma, increased tumor-associated macrophage infiltration was associated with inferior outcome[78]. An interesting question to be resolved is whether also in PTLD macrophages influence prognosis.

**BL**

**Cell of origin:** BL is a highly aggressive lymphoma characterized by a high mitotic rate and numerous tingible body macrophages (loaded with debris from apoptotic cells). Three clinical variants of BL are recognized: Endemic BL (with a high prevalence in equatorial Africa), sporadic BL (prevalent in Western countries) and immunodeficiency-associated BL (primarily affecting human immunodeficiency virus (HIV) infected patients, but also reported in transplant recipients). The association with EBV is different for the three subtypes and strongest in the endemic variant (nearly 100% EBV+), followed by the immunodeficiency-associated variant (30%-80% EBV+) and sporadic BL (15%-20% EBV+). Notably, EBV+ Burkitt lymphoma is the EBV transformed tumor with the most limited expression of viral proteins (typically only EBNA1 is expressed)[79].

BL is classically thought to arise from a GCB cell however analysis of the SHM patterns in a series of endemic, sporadic and AIDS-related BL suggested that BL may arise from different stages of B-cell differentiation, associated with the EBV status. EBV+ BL were highly mutated and may derive from a late antigen-selected GC B-cell or memory B-cell for EBV+ BL. EBV BL on the other hand harbored only a limited number of mutations and may arise from an early centroblast[80].

**Genetics:** The hallmark of BL is the presence of translocations involving MYC [with IgH: t(8;14)(q24;q32)] which are also found in PTLD with Burkitt morphology[37]. It is highly debated whether MYC-translocation-positive BL is a form of true molecular BL[81]. In a recent study, an 11q aberration was detected in MYC-negative high-grade B-cell lymphomas resembling BL (both at the morphological as well as the molecular level, but without MYC rearrangement)[83]. In our series of IC- and PT-BL this peculiar 11q gain/loss was particularly frequent in PT cases lacking MYC translocation, suggesting a different pathogenesis of BL in different immune settings. However, a recent study demonstrated that 11q gain/loss and MYC translocation are not mutually exclusive[83]. It is possible that both aberrations have complementary effects: Integrated analysis of genomic and transcriptomic data of our series of MYC translocation-positive and -negative cases suggested that the 11q-gain/loss is a molecular variant of MYC rearrangement, affecting similar pathways.

**Gene expression profile and microenvironment:** In contrast to PT-DLBCL, the gene expression profile of EBV+ and EBV BL is not significantly different, indicating that MYC signaling rather than the EBV status has the major impact on the expression profile[84]. BL lesions are composed of very little stromal infiltrate indicating that BL tumor cells are poorly immunogenic. Remarkably, even when BL cells express highly immunogenic EBV antigens EBNA3A, -3B, and -3C[85] or foreign antigens are introduced by a recombinant virus[86] they are not recognized by antigen-specific CTL clones. An in vitro study pointed to a crucial role of MYC. It was demonstrated that this oncogene negatively regulates NF-kB and interferon signaling by suppression of STAT1 resulting in decreased immunogenicity[87].

**PBL**

**Cell of origin:** PBL is an aggressive terminally differentiated variant of DLBCL that has many morphological and immunophenotypic characteristics in common with a plasmablast (a B-cell in the final stages of plasma cell differentiation). PBL typically arises in the oral cavity of HIV patients[88] but has also been reported in immunocompetent individuals[89] and transplant recipients[88].

In a series of AIDS-related PBL (10/12 were EBV+), evidence of somatic hypermutation was found in only 4/10 analyzed cases suggesting histogenetic heterogeneity of PBL[90].

**Genetics:** Currently, very little is known about the molecular-genetic basis that drives PBL. One study showed that up to 47% of EBV+ AIDS-related PBLs are marked by MYC translocations[91]. Array-comparative genomic hybridization involving 16 PBL demonstrated that, despite the high degree of immunophenotypic similarity between PBL and plasma cell myeloma (PCM)[92], the genomic aberration pattern of PBL is more similar to DLBCL than to PCM[93].

**Gene expression profile and microenvironment:** A gene expression profiling study reported that PBL was more similar to extrasosseous plasmacytoma than to DLBCL[94] reflecting the plasma cell immunophenotypic features of these malignancies. No significant differences were found between EBV+ and EBV PBL, however this may be related to the small sample size.

Reanalysis of our gene expression data (3 EBV+ PT-PBL vs 20 EBV+ PT-DLBCL, fold change 2, FDR < 0.05[95]) confirmed enhanced MYC signaling and demonstrated unfolded protein response endoplasmic reticulum stress signaling in PBL (unreported data). These findings
provide an explanation for the success of bortezomib treatment in PBL case reports\cite{96,97} and suggest that BET bromodomain inhibitors may represent a potential new therapeutic strategy, as has been successfully demonstrated in experimental models of multiple myeloma\cite{98}.

As for EBV+ DLBCL, EBV+ PBL may be associated with a tolerant microenvironment. In a recent clinicopathological analysis of 82 PBL arising in HIV+ and HIV- patients particularly EBV+ tumors highly expressed PDL1-PD1 in both malignant cells and microenvironment\cite{99}.

CONCLUSION

The findings presented in this review underscore the heterogeneous nature of PTLD and could serve as a basis to revise the current PTLD classification. We propose that within the group of monomorphic PTLD, the different histological lymphoma entities (DLBCL, BL, PBL) should be distinguished. We suggest that also the EBV status should be included to further stratify PTLD patients in future studies and clinical trials.

ACKNOWLEDGMENTS

The authors would like to acknowledge the other members of the “Leuven PTLD consortium”, in particular Bittoun E, Dierickx D, Finate Ferreiro J, Gheysens O, Marcelis L, Verhoef G and Wlodarska I.

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