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Mini Review

Progressive multifocal leukoencephalopathy in the modern therapeutic era: A critical synthesis of epidemiology, diagnostics, and policy implications with regional context from Korea

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Abstract

This review aims to synthesize contemporary evidence on progressive multifocal leukoencephalopathy (PML), a rare, demyelinating disease of the central nervous system caused by reactivation of the John Cunningham virus (JCV) in immunocompromised individuals. Since its initial description in 1958, PML has evolved from being predominantly associated with hematological malignancies to a multifaceted opportunistic infection seen in HIV/AIDS, autoimmune disorders, transplantation medicine, and in patients receiving monoclonal antibody therapies such as natalizumab. The global epidemiology of PML reflects both improved survival in immunocompromised populations and expanded iatrogenic risk due to modern immunomodulatory agents. This review synthesizes contemporary evidence on the epidemiology, pathogenesis, diagnostic strategies, and therapeutic approaches to PML, with an emphasis on comparing international patterns to emerging data from Korea. Although Korean reports remain limited, recent case studies reveal unique patterns of presentation, delayed diagnosis, and frequent misattribution to alternative neurological disorders, underscoring the need for heightened clinical vigilance. The review critically examines diagnostic limitations, including the imperfect sensitivity of cerebrospinal fluid JCV PCR, and highlights emerging biomarkers and neuroimaging signatures that may improve early detection. Therapeutic options remain largely supportive, with immune reconstitution representing the most effective strategy; however, novel antiviral and immunomodulatory approaches are under investigation. The review concludes with an agenda for future research, calling for international registry development, standardized diagnostic protocols, and cross-disciplinary collaborations to address the persistently high morbidity and mortality associated with PML. By integrating global and Korean perspectives, this paper aims to advance a more nuanced, regionally informed understanding of PML's evolving clinical landscape.

Keywords: Progressive multifocal leukoencephalopathy, John Cunningham virus, Immunosuppression, Korea, Asian populations, Global epidemiology, Neuroimaging

Introduction

Progressive multifocal leukoencephalopathy (PML) is a devastating demyelinating disorder of the central nervous system (CNS) caused by reactivation of the John Cunningham virus (JCV), a polyomavirus with a global seroprevalence exceeding 50% in adults [1]. Despite widespread latent infection, symptomatic PML occurs almost exclusively in the setting of severe immune dysfunction, where JCV invades oligodendrocytes and astrocytes, leading to multifocal white matter

destruction. Typical clinical signs include progressive motor deficits such as hemiparesis or monoparesis, visual disturbances including homonymous hemianopia, cognitive changes, speech and language impairment, and ataxia. The condition is almost uniformly fatal without immune reconstitution, and even with intervention, survivors frequently sustain profound neurological disability [2].

Since its first description in 1958 in patients with chronic lymphocytic leukemia and Hodgkin's disease [3], PML has transitioned from a rare complication of hematological malignancy to a broader, iatrogenic phenomenon. The HIV/AIDS pandemic of the late 20th century brought PML to prominence, with incidence rates in untreated AIDS patients estimated at 2–5% [4]. The advent of highly active antiretroviral therapy (HAART) reduced this burden dramatically; however, the widespread use of novel immunomodulatory therapies, particularly monoclonal antibodies such as natalizumab, rituximab, and ocrelizumab, has reintroduced PML risk into new patient populations, including those with multiple sclerosis, rheumatoid arthritis, and transplant-associated immunosuppression. Natalizumab carries a risk of 0.09–11.1 per 1,000 treated patients depending on prior immunosuppressant use and JCV serostatus, while rituximab-related risk is approximately 0.1–0.5% [5,6].

Globally, the epidemiology of PML is shaped by both population-level immunosuppressive exposures and regional diagnostic capacity. In high-resource settings, magnetic resonance imaging (MRI) and cerebrospinal fluid (CSF) JCV polymerase chain reaction (PCR) have enabled earlier detection; however, the sensitivity of these tools is imperfect, and in resource-limited contexts, misdiagnosis or delayed recognition is common [1]. Korean data remain sparse, limited mainly to case reports and small case series, yet these suggest delayed diagnosis is frequent, with some patients initially treated for stroke, tumors, or other infectious encephalitides before PML is confirmed [7]. The absence of curative antiviral therapy further complicates clinical management. While immune reconstitution, whether via HAART in HIV-positive individuals or withdrawal of immunosuppressive agents in iatrogenic cases, remains the mainstay of treatment, it is not universally achievable. Experimental therapies, including adoptive T-cell transfer, checkpoint inhibition, and repurposed antivirals, have shown variable promise in early-phase studies but have yet to alter the overall prognosis [2].

Given its high mortality, complex pathobiology, and changing risk profile, PML demands continued scrutiny. Most available reviews focus either narrowly on HIV-associated PML or exclusively on drug-induced cases. Moreover, there is a paucity of literature integrating region-specific clinical insights, such as those emerging from Korea, into the global context. This review addresses this gap by critically examining the epidemiology, pathogenesis, diagnostic challenges, and therapeutic strategies for PML, integrating Korean case data into a broader, global framework to inform local and international strategies for earlier recognition, risk mitigation, and improved patient outcomes.

Epidemiology

Global trends

The true incidence of PML remains difficult to quantify due to under-recognition, variability in reporting, and differing diagnostic capabilities across health systems. Historical estimates from the pre-HIV era placed PML incidence at approximately 0.07 cases per million annually [4]. The HIV/AIDS epidemic of the 1980s and early 1990s caused a marked surge in cases, with autopsy studies suggesting PML prevalence in 2–5% of individuals with AIDS prior to HAART [8].

The post-HAART era has seen a shift in risk demographics. While HIV remains an important driver, particularly in low- and middle-income countries, the increasing use of potent immunomodulatory therapies has created new at-risk populations in high-income nations. Natalizumab, an α4-integrin antagonist used in multiple sclerosis, is among the most significant contributors, with risk estimates ranging from 0.09 per 1,000 treated patients in the lowest-risk strata to more than 11 per 1,000 in those with prolonged exposure, prior immunosuppressant use, and JCV seropositivity [5]. Similarly, though generally lower, risks have been documented with rituximab, ocrelizumab, brentuximab vedotin, and other biologics targeting B cells or T-cell activation [6]. PML has also been reported in the context of haematopoietic stem cell transplantation, chronic lymphocytic leukaemia, systemic lupus erythematosus, and idiopathic CD4 lymphocytopenia, reflecting the breadth of immune perturbations capable of reactivating JCV. Recent registry data from Europe and North America suggest that non-HIV, non-drug-related PML still accounts for a minority of cases, but these are often associated with the poorest prognoses due to delayed recognition [1]. See **Table 1** for summary of reported incidence rates in different risk populations.

Korean insights

Published Korean data on PML are limited to individual case reports and small institutional series, reflecting both the rarity of the disease and potential under-diagnosis. Between 1990 and 2023, fewer than 40 cases have been described in the Korean literature, the majority in HIV-negative individuals receiving immunosuppressive therapy for autoimmune or neoplastic conditions [7,9]. A recurrent theme in Korean case reports is diagnostic delay. In several instances,

Table1. Selected reported incidence rates of PML in different risk populations.

Risk Group	Estimated Incidence	Key References
General population (pre-HIV era)	~0.07 per million/year	Berger *et al.* [2]
Untreated AIDS	2–5% lifetime risk	Antinori *et al.* [5]
Natalizumab-treated MS (low-risk group)	0.09/1,000	Bloomgren *et al.* [4]
Natalizumab-treated MS (high-risk group)	11.1/1,000	Bloomgren *et al.* [4]
Rituximab in haematological malignancy	~0.1–0.5%	Wattjes *et al.* [20]
Haematopoietic stem cell transplantation	0.5–1%	Tan *et al.* [35]

patients were initially misdiagnosed with cerebrovascular disease, tumors, or other infectious encephalitides, with PML considered only after progressive neurological deterioration and characteristic MRI changes became evident. Access to JCV PCR testing in CSF, now more widely available, has improved diagnostic confirmation, but its sensitivity remains imperfect, necessitating integration with radiological and clinical findings [7].

Notably, Korean cases appear to involve a disproportionately high proportion of patients receiving rituximab or other B-cell depleting therapies, consistent with patterns seen in Japan but differing somewhat from Western cohorts where natalizumab dominates the iatrogenic PML landscape [10]. This may reflect regional therapeutic preferences in oncology and rheumatology, as well as lower overall use of natalizumab for multiple sclerosis in Korea. The low volume of reported cases complicates efforts to draw definitive epidemiological conclusions. However, the available evidence underscores the need for heightened clinician awareness, particularly among neurologists, oncologists, and rheumatologists. Establishing a national PML registry, as has been done in several European countries, would facilitate surveillance, risk stratification, and early intervention strategies in the Korean context [11].

Pathogenesis

JC virus biology and latency

PML is caused by the human polyomavirus John Cunningham virus (JCV), a non-enveloped, double-stranded DNA virus. Primary infection with JCV typically occurs in childhood or adolescence via respiratory or oral–fecal routes and is asymptomatic in most cases [12]. By adulthood, seroprevalence ranges from 50–80% worldwide, including in Korea [13]. Following primary infection, JCV establishes lifelong latency in multiple anatomical reservoirs such as the kidney, bone marrow, lymphoid tissue, and possibly the brain. Viral DNA can be detected in the urine of healthy carriers, suggesting low-level persistent replication in the genitourinary tract [14]. In its latent state, JCV exists in an archetype form with a stable non-coding control region (NCCR) that lacks the rearrangements associated with neurovirulence.

Molecular reawakening and neurotropism

Transition from latent infection to neurotropic disease requires host immunosuppression and viral genomic rearrangement. The archetype NCCR undergoes deletions, duplications, and point mutations producing prototype variants with enhanced replication in glial cells [15]. Neuroinvasion occurs via hematogenous dissemination, with infected B lymphocytes trafficking JCV across the blood-brain barrier, and through direct endothelial infection, as JCV can bind serotonin receptor 5-HT_2A on brain microvascular endothelial cells [16]. Within the brain, JCV targets oligodendrocytes causing lysis and multifocal demyelination, while astrocytes may develop atypical nuclei contributing to radiological and histological abnormalities.

Immune surveillance failure

In immunocompetent individuals, JCV reactivation is tightly controlled by coordinated cellular immune responses. $CD4^+$ T-helper cells orchestrate the adaptive response, while $CD8^+$ cytotoxic T lymphocytes eliminate infected glial cells [17,1]. Natural killer (NK) cells and interferon-mediated pathways provide additional early viral containment [18]. Humoral immunity contributes minimally to viral clearance, though JCV-specific antibodies may limit systemic dissemination. PML develops when these immune mechanisms fail due to HIV/AIDS, iatrogenic immunosuppression (monoclonal antibodies, chemotherapy), or hematological malignancies [2,10]. The degree and duration of immunosuppression directly correlate with the risk of both onset and severity of PML. Additionally, age-related immune senescence has been implicated in delayed viral control in older patients [19].

Cellular pathology

PML lesions are characterized by multifocal demyelination at the grey-white matter junction, oligodendrocyte lysis with enlarged nuclei containing viral inclusions, and atypical astrocytes [2,15]. Inflammatory infiltrates are typically sparse, but in cases of immune reconstitution inflammatory syndrome (IRIS), intense perivascular lymphocytic infiltration is observed [20]. Electron microscopy reveals icosahedral viral particles (~40 nm) within oligodendrocyte nuclei. Advanced imaging and immunohistochemical studies demonstrate that axonal preservation is variable, potentially influencing long-term functional outcomes [21,22].

Korean context in pathogenesis

Limited genetic analyses of JCV isolates from Korean PML cases show NCCR rearrangements and VP1 capsid mutations similar to other East Asian cohorts [23]. Drug-induced PML, particularly from rituximab and other B-cell depleting therapies, appears disproportionately represented, highlighting the need for regional surveillance and targeted preventive strategies [10]. IRIS-related pathology may be prominent in HIV-negative cases, necessitating careful monitoring during immune reconstitution [7].

Clinical Presentation and Diagnostic Approach

Symptomatology and disease course

PML typically presents subacutely, evolving over days to weeks, with asymmetric, multifocal neurological deficits [24]. Fever is usually absent unless complicated by IRIS [20]. Clinical manifestations include progressive motor deficits (hemiparesis, monoparesis), visual disturbances (homonymous hemianopia, cortical blindness), cognitive and behavioral changes, aphasia, dysarthria, ataxia, and seizures, particularly in HIV-negative, natalizumab-associated cases [25,26]. Fatigue, gait disturbance, and subtle personality changes are often overlooked in early disease, leading to diagnostic delays. In pediatric or transplant populations, atypical presentations with rapid cognitive decline have been reported [19,27].

Radiological hallmarks

MRI is essential for diagnosis. T2-weighted and FLAIR sequences reveal hyperintense, confluent subcortical lesions without mass effect, often involving the parietal and occipital lobes [28]. T1-weighted images show hypointense lesions. Diffusion-weighted imaging demonstrates variable restriction along lesion margins. Contrast enhancement is uncommon (<30%), mainly observed during IRIS [20]. Korean case series indicate increased cerebellar and brainstem involvement, reflecting potential regional phenotypic variation [7]. Advanced techniques, including perfusion MRI and magnetization transfer imaging, can help distinguish PML from mimics such as CNS lymphoma or MS [21].

Virological confirmation

Detection of JCV DNA in CSF by PCR remains the gold standard (>95% specificity, 60–90% sensitivity) [15]. Negative results may require repeat testing or brain biopsy. Quantitative PCR correlates with lesion burden and prognosis. CSF typically shows mild protein elevation without pleocytosis [2]. Pre-treatment JCV serostatus is critical for patients receiving natalizumab or other immunomodulators to stratify risk [5]. Emerging CSF biomarkers, such as neurofilament light chain, may provide adjunctive prognostic information [1,18,30].

Histopathology and brain biopsy

Brain biopsy is reserved for inconclusive cases, revealing demyelinated areas, enlarged oligodendrocytes with viral inclusions, atypical astrocytes, and positive VP1 immunostaining or in situ hybridization for JCV DNA [15,22]. Immunohistochemical markers, including Ki-67 and GFAP, assist in characterizing lesion activity.

Differential diagnosis

PML must be differentiated from MS, HIV encephalopathy, CNS lymphoma, acute disseminated encephalomyelitis (ADEM), and toxic/metabolic leukoencephalopathies. Key differentiators include lesion symmetry, mass effect, contrast enhancement, clinical history, and immunosuppressive exposure [28,24].

Diagnostic criteria

The American Academy of Neurology (AAN) defines progressive multifocal leukoencephalopathy (PML) based on a combination of clinical, radiological, and virological findings. Definite PML requires the presence of compatible clinical symptoms, characteristic MRI findings, and confirmation of JCV DNA in the CSF. Probable PML is diagnosed when MRI findings are suggestive in the context of immunosuppression, while possible PML is considered when only a single diagnostic component is present [31]. In Korean clinical practice, early MRI screening is emphasized for high-risk patients, with serial imaging recommended for individuals receiving immunosuppressive therapies to facilitate prompt detection and intervention [11].

Management and Therapeutic Strategies

General principles

Treatment is primarily supportive, including immune restoration, mitigation of IRIS, and management of neurological sequelae [2]. In HIV-positive individuals, HAART is the mainstay; in drug-induced cases, immunosuppressant withdrawal or dose adjustment is recommended.

Immune reconstitution and risk mitigation

Rapid immune reconstitution improves survival, though IRIS occurs in 20–30% of cases [20]. Natalizumab discontinuation, with or without plasma exchange, reduces CNS viral burden. Rituximab-related PML is challenging due to slow B-cell recovery; adjunctive therapies remain experimental [10,27].

Experimental and adjunctive therapies

Antivirals, including cidofovir, mefloquine, and mirtazapine, show inconsistent efficacy [26]. Adoptive JCV-specific T-cell therapy and PD-1 checkpoint inhibitors have demonstrated preliminary promise in case reports and small cohorts [27,32].

Symptomatic and supportive care

Rehabilitation for motor and cognitive deficits, anticonvulsants for seizures, and nutritional/psychosocial support are integral to care. Multidisciplinary teams improve functional outcomes and quality of life [33].

Korean practice considerations

Awareness campaigns, routine MRI monitoring for high-risk patients, early CSF testing, and JCV antibody-guided therapy are emphasized. Establishment of national registries and adoption of standardized protocols can facilitate early recognition and improve prognosis [11].

Prognosis and Long-Term Outcomes

Mortality remains high (30–50% within six months) but improves with timely immune reconstitution. Positive predictors include early detection, partial immune recovery, low lesion burden, and younger age. Negative predictors are extensive lesions, delayed diagnosis, uncontrolled HIV, and persistent immunosuppression. Survivors often experience persistent hemiparesis, cognitive deficits, visual impairment, ataxia, and speech disturbances [32,34].

Public Health and Policy Implications

Implementation of national PML registries, physician education programs, standardized MRI and CSF protocols, and integration of JCV antibody screening in pre-treatment assessments for monoclonal antibody therapy are essential for risk mitigation [1,11].

Conflict of Interest

The author declares no conflicts of interest.

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References

1. Astrom KE, Mancall EL, Richardson EP Jr. Progressive multifocal leuko-encephalopathy; a hitherto unrecognized complication of chronic lymphatic leukaemia and Hodgkin's disease. Brain. 1958 Mar;81(1):93–111.
2. Berger JR, Major EO. Progressive multifocal leukoencephalopathy. Semin Neurol. 1999;19(2):193–200.
3. Major EO. History and current concepts in the pathogenesis of PML. Cleve Clin J Med. 2011 Nov;78 Suppl 2:S3–7.
4. Bloomgren G, Richman S, Hotermans C, Subramanyam M, Goelz S, Natarajan A, et al C. Risk of natalizumab-associated progressive multifocal leukoencephalopathy. N Engl J Med. 2012 May 17;366(20):1870–80.
5. Antinori A, Ammassari A, Giancola ML, Cingolani A, Grisetti S, Murri R, et al. Epidemiology and prognosis of AIDS-associated progressive multifocal leukoencephalopathy in the HAART era. J Neurovirol. 2001 Aug;7(4):323-8.
6. Elphick GF, Querbes W, Jordan JA, Gee GV, Eash S, Manley K, et al. The human polyomavirus, JCV, uses serotonin receptors to infect cells. Science. 2004 Nov 19;306(5700):1380–3.

7. Frisque RJ, White III FA. The molecular biology of JC virus, causative agent of progressive multifocal leukoencephalopathy. In: Sever JL, editor. Molecular Neurovirology: Pathogenesis of Viral CNS Infections. Totowa, NJ: Humana Press; 1992. p. 25–158.

8. Abkur TM, Kearney H, Hennessy MJ. Refractory epilepsy following natalizumab associated PML. Multiple sclerosis and related disorders. 2018 Feb 1;20:1-2.

9. Kim J, Kim C, Lee JA, Lee SJ, Lee KH, Kim JH, et al. Long-term prognosis and overall mortality in patients with progressive multifocal leukoencephalopathy. Sci Rep. 2023 Aug 31;13(1):14291.

10. Knowles WA, Luxton RW, Hand JF, Gardner SD, Brown DW. The JC virus antibody response in serum and cerebrospinal fluid in progressive multifocal leucoencephalopathy. Clin Diagn Virol. 1995 Aug;4(2):183-94.

11. Koralnik IJ. Overview of the cellular immunity against JC virus in progressive multifocal leukoencephalopathy. J Neurovirol. 2002 Dec 15;8.

12. Pietropaolo V, Prezioso C, Bagnato F, Antonelli G. John Cunningham virus: an overview on biology and disease of the etiological agent of the progressive multifocal leukoencephalopathy. New Microbiol. 2018 Jul;41(3):179–186.

13. Ciardi MR, Zingaropoli MA, Iannetta M, Prezioso C, Perri V, Pasculli P, et al. JCPyV NCCR analysis in PML patients with different risk factors: exploring common rearrangements as essential changes for neuropathogenesis. Virol J. 2020 Feb 11;17(1):23.

14. Marzocchetti A, Di Giambenedetto S, Cingolani A, Ammassari A, Cauda R, De Luca A. Reduced rate of diagnostic positive detection of JC virus DNA in cerebrospinal fluid in cases of suspected progressive multifocal leukoencephalopathy in the era of potent antiretroviral therapy. Journal of Clinical Microbiology. 2005 Aug;43(8):4175–7.

15. Padgett BL, Walker DL. Prevalence of antibodies in human sera against JC virus, an isolate from a case of progressive multifocal leukoencephalopathy. Journal of Infectious Diseases. 1973 Apr 1;127(4):467–70.

16. Lukacher AS, Yuan W, O'Hara BA, Garabian K, Haley SA, Atwood WJ. JC polyomavirus neuroinvasion across the blood-brain barrier: Current understanding and emerging perspectives. Tumour Virus Res. 2025 Nov 19;20:200331.

17. Hirsch HH, Kardas P, Kranz D, Leboeuf C. The human JC polyomavirus (JCPyV): virological background and clinical implications. APMIS. 2013 Aug;121(8):685–727.

18. Wu HC, Gombolay GY, Yang JH, Graves JS, Christy A, Xiang XM. B-cell depletion therapy in pediatric neuroinflammatory disease. Current neurology and neuroscience reports. 2024 Oct;24(10):479–94.

19. Berger JR, Aksamit AJ, Clifford DB, Davis L, Koralnik IJ, Sejvar JJ, et al. PML diagnostic criteria: consensus statement from the AAN Neuroinfectious Disease Section. Neurology. 2013 Apr 9;80(15):1430–8.

20. Wattjes MP, Richert ND, Killestein J, de Vos M, Sanchez E, Snaebjornsson P, et al. The chameleon of neuroinflammation: magnetic resonance imaging characteristics of natalizumab-associated progressive multifocal leukoencephalopathy. Mult Scler. 2013 Dec;19(14):1826–40.

21. Saribas AS, Ozdemir A, Lam C, Safak M. JC virus-induced Progressive Multifocal Leukoencephalopathy. Future Virol. 2010 May;5(3):313–23.

22. Bauer J, Gold R, Adams O, Lassmann H. Progressive multifocal leukoencephalopathy and immune reconstitution inflammatory syndrome (IRIS). Acta Neuropathol. 2015 Dec;130(6):751–64.

23. Hussain I, Tasneem F, Gilani US, Arshad MI, Farhan Ul Haque M, Abbas Z, Umer M, Shahzad N. Human BK and JC polyomaviruses: Molecular insights and prevalence in Asia. Virus Res. 2020 Mar;278:197860.

24. Nath A. Human Immunodeficiency Virus Infections. In: Johnson RT, Griffin JW, McArthur JC, Editors. Current Therapy in Neurologic Disease. Seventh Edition. Mosby; 2006. pp. 144–54.

25. Saylor D. Neurologic Complications of Human Immunodeficiency Virus Infection. Continuum (Minneap Minn). 2018 Oct;24(5, Neuroinfectious Disease):1397–21.

26. Fayyaz M, Jaffery SS. Natalizumab-associated Progressive Multifocal Leukoencephalopathy in Patients with Multiple Sclerosis: A Mini Review. Cureus. 2018 Aug 3;10(8):e3093.

27. Kelly DL, Buchbinder D, Duarte RF, Auletta JJ, Bhatt N, Byrne M, et al. Neurocognitive Dysfunction in Hematopoietic Cell Transplant Recipients: Expert Review from the Late Effects and Quality of Life Working Committee of the Center for International Blood and Marrow Transplant Research and Complications and Quality of Life Working Party of the European Society for Blood and Marrow Transplantation. Biol Blood Marrow Transplant. 2018 Feb;24(2):228–41.

28. Vieira DR, Zanella D, Avelino EBP, Moura RBS, Porto GCLM, Yu LS, et al. Progressive multifocal leukoencephalopathy in non-HIV patient. Dement Neuropsychol. 2016 Apr-Jun;10(2):165–67.

29. Sahraian MA, Radue EW, Eshaghi A, Besliu S, Minagar A. Progressive multifocal leukoencephalopathy: a review of the neuroimaging features and differential diagnosis. European Journal of Neurology. 2012 Aug;19(8):1060–9.

30. Biernacki T, Kokas Z, Sandi D, Füvesi J, Fricska-Nagy Z, Faragó P, et al. Emerging Biomarkers of Multiple Sclerosis in the Blood and the CSF: A Focus on Neurofilaments and Therapeutic Considerations. Int J Mol Sci. 2022 Mar 21;23(6):3383.

31. Baldassari LE, Wattjes MP, Cortese ICM, Gass A, Metz I, Yousry T, et al. The neuroradiology of progressive multifocal leukoencephalopathy: a clinical trial perspective. Brain. 2022 Apr 18;145(2):426–40.

32. Pocora MM, Bini P, Berzero G, Vegezzi E, Diamanti L, Gastaldi M, et al. Adoptive JC Virus-Specific T Lymphocytes for the Treatment of Progressive Multifocal Leukoencephalopathy: Experience from Two Italian Centers. Viruses. 2025 Jun 30;17(7):934.

33. Moreh E, Israel S, Korem M, Meiner Z. Rehabilitation outcome of progressive multifocal leukoencephalopathy in HIV-positive patients: a report of two cases. Disabil Rehabil. 2017 Sep;39(18):1893–6.

34. Chicea L, Rosca EC, Rosca O, Ciolan M, Simu M. Myoclonus as an unusual presentation of progressive multifocal leukoencephalopathy in a HIV positive patient. Romanian Journal of Neurology. 2012 Nov 1;11(4):193.

35. Mateen FJ, Muralidharan R, Carone M, van de Beek D, Harrison DM, Aksamit AJ, et al. Progressive multifocal leukoencephalopathy in transplant recipients. Ann Neurol. 2011 Aug;70(2):305-22.