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Borna disease virus

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Borna disease virus, a negative-strand RNA virus, infects a wide variety of warm-blooded animals. Depending on the age of the host and the integrity of its immune response, infection may be asymptomatic or cause a broad spectrum of behavioral disorders. Unusual features of Borna disease virus biology include nuclear localization of replication and transcription; diverse strategies for regulation of gene expression; and interaction with signaling pathways resulting in subtle neuropathology. Although the question of human infection remains unresolved, burgeoning interest in this unique pathogen has provided tools for exploring the pharmacology and neurochemistry of neuropsychiatric disorders potentially linked to infection. Analysis of rodent models of infection has yielded insights into mechanisms by which neurotropic agents and/or immune factors may impact developing or mature central nervous system circuitry to effect complex disturbances in movement and behavior. *Journal of NeuroVirology* (2003) **9,** 259–273.

Keywords: animal model; Borna disease virus; neuropharmacology; neuropsychiatric disease; RNA virus

Introduction

It is more than a decade since nucleic acids of Borna disease virus (BDV) were cloned (Lipkin *et al*, 1990; VandeWoude *et al*, 1990). The BDV subtractive cloning project, initiated to develop the tools required to assess the role of BDV in human disease, opened up a new field in molecular virology and pathogenesis, but failed in its primary objective. Despite the introduction of diagnostic polymerase chain reaction (PCR) assays, and serologic methods based on recombinant proteins and peptides, the epidemiology of BDV remains obscure and controversial (Bode *et al*, 2001; Lipkin *et al*, 2001; Staeheli and Lieb, 2001). This review summarizes recent advances in BDV research, with emphasis on molecular biology; virus/host cell interactions; epidemiologic data indicating the occurrence of natural BD outside of endemic Central European areas, and highlighting controversy regarding its role in human neuropsychiatric disease; and experimental models of infection that provide insights into developmental neurobiology.

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Molecular biology

Borna disease virus (BDV) is the prototype of a new family Bornaviridae, genus *Bornavirus*, within the nonsegmented negative-strand RNA viruses (order Mononegavirales). Although similar in genomic organization to other nonsegmented negative-strand (NNS) RNA viruses, BDV is distinctive in its nuclear localization of replication and transcription (Briese *et al*, 1992; Carbone *et al*, 1991a; Cubitt and de la Torre, 1994). This feature is shared with plant nucleorhabdoviruses; it is, however, unique amongst NNS RNA animal viruses. The molecular biology of BDV is complex, and includes overlap of open reading frames (ORFs) and transcription units,

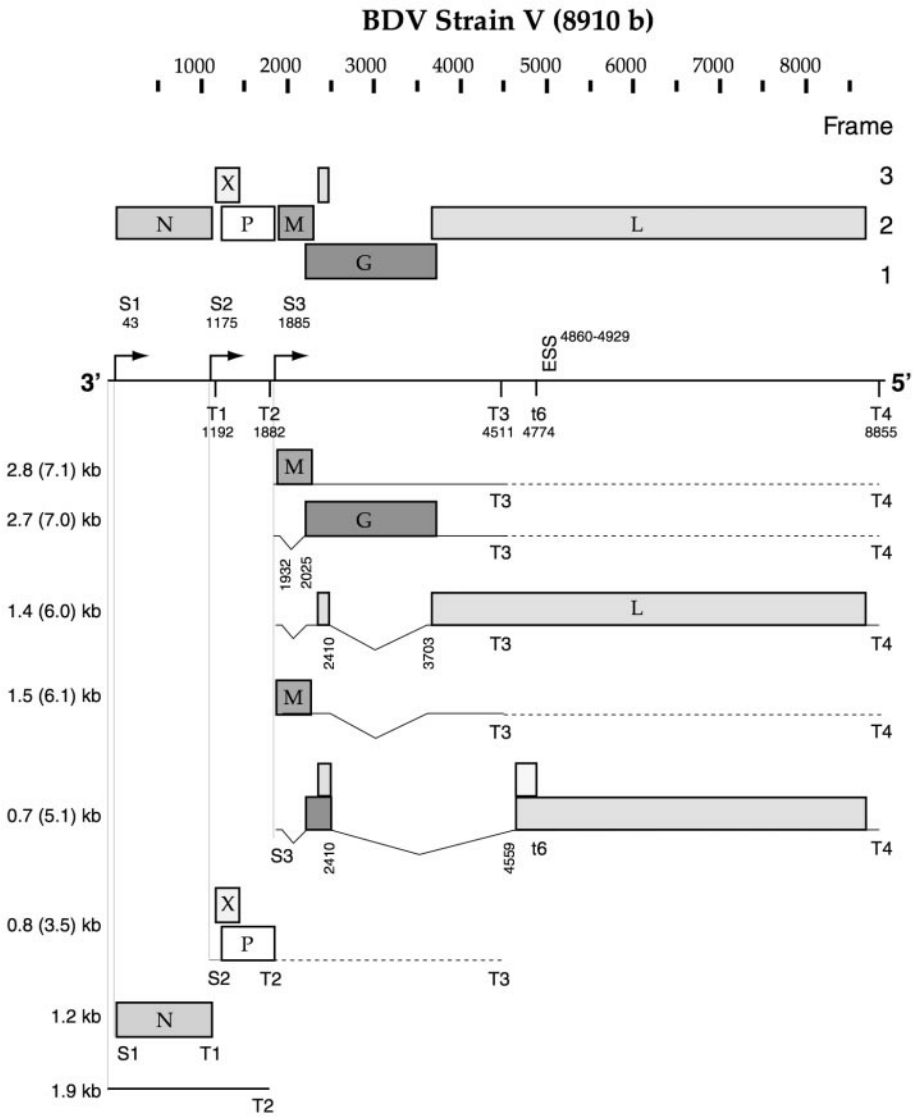

Figure 1 BDV genomic map and transcripts. *Abbreviations*: S1 through S3, initiation sites of transcription; T1 through T4, and t6, termination sites of transcription. Readthrough at termination signals T2 and T3 are indicated by dashed lines; ESS, exon-splicing suppressor.

transcriptional read-through of termination signals, and differential use of initiation codons (Briese *et al*, 1994; Schneemann *et al*, 1994, 1995). BDV uses cellular splicing machinery to generate some of its mRNAs (Figure 1) (Cubitt *et al*, 1994; Schneider *et al*, 1994b), an aspect consistent with its nuclear localization of transcription and replication. Although splicing is also found in Orthomyxoviridae (segmented, negative-strand RNA viruses), it is unprecedented in Mononegavirales.

BDV encodes at least six proteins. Five proteins correspond to the nucleoprotein (N, p40), phosphoprotein (P, p23), matrix protein (M, p16), glycoprotein (G, p57), and L-polymerase (L, p190) found in other Mononegavirales. The sixth, p10 (X protein), does not have a clear homologue in other NNS RNA viral systems. Data on alternative splicing indicate that the repertoire of BDV proteins may be larger still. Alternative splicing is a cardinal feature of BDV molecular biology. Splicing to remove approximately 100 bp of M ORF sequence (intron I; Cubitt *et al*, 1994; Schneider *et al*, 1994b) from some mRNAs allows expression of the surface glycoprotein G by leaky ribosomal scanning (Schneider *et al*, 1997b); splicing to remove approximately 1.3 kb of G ORF sequence allows fusion of a small upstream ORF with the large, last ORF (intron II; Cubitt *et al*, 1994; Schneider *et al*, 1994b), to generate the full-length L-polymerase protein (Walker *et al*, 2000). Recently, an additional splice acceptor site (nucleotide [nt] 4559) has been characterized that may allow translation of two additional viral proteins (see Figure 1; Cubitt *et al*, 2001; Tomonaga *et al*, 2000). However, because this splice acceptor site is not conserved in the BDV No/98

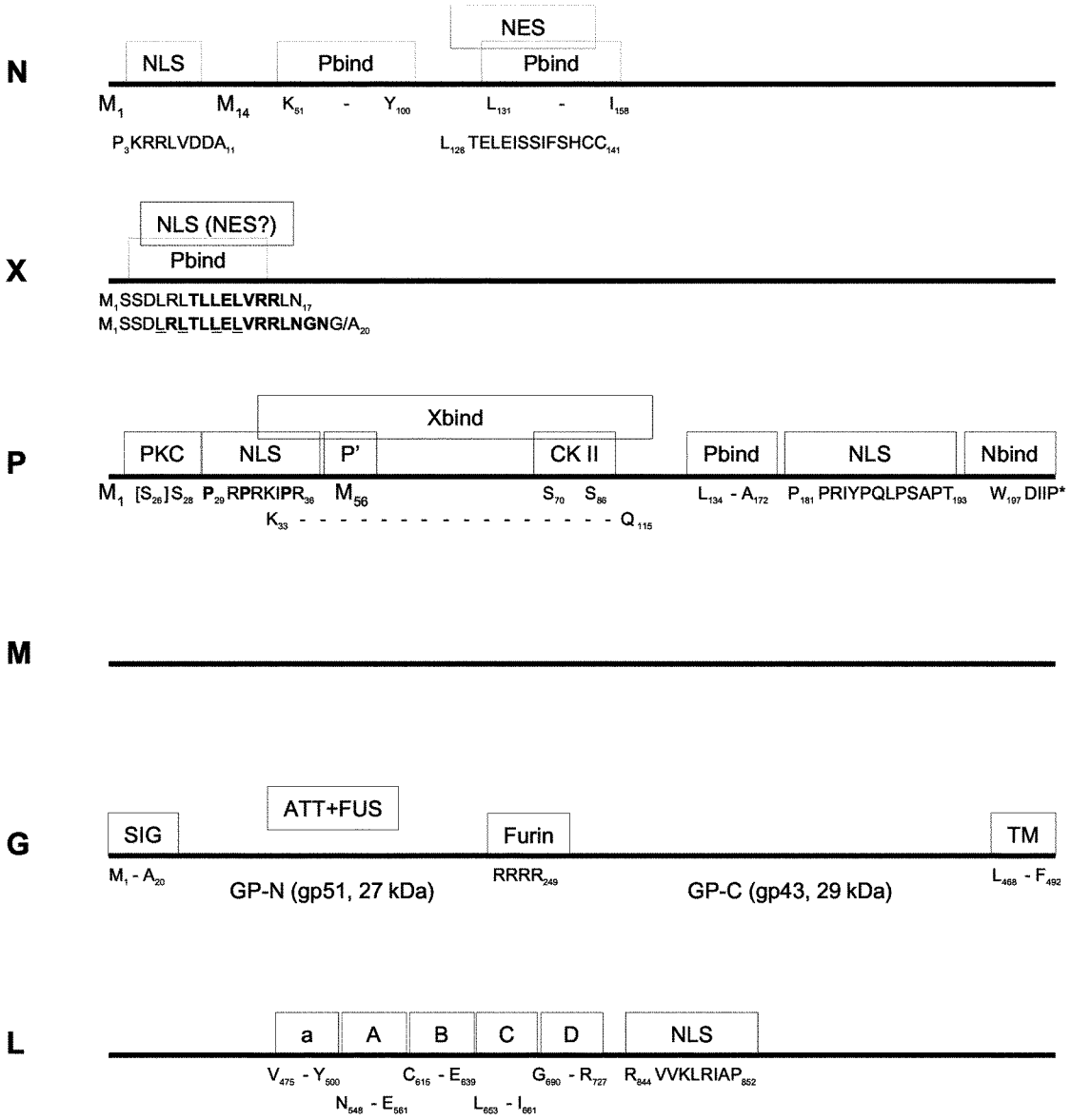

Figure 2 Functional motifs identified in BDV proteins. *Abbreviations*: M1 and M14 in N, and M1 and M56 in P, represent start sites of p40 and p38, and P or P′ respectively; NLS, nuclear localization signal; NES, nuclear export signal; Pbind, P binding site; Xbind, X binding site; Nbind, N binding site; PKC, PKCε phosphorylation site; CKII, casein kinase phosphorylation site; SIG, signal peptide; TM, transmembrane domain; ATT + FUS, attachment and fusion domain; Furin, furin cleavage site; a, A, B, C, D, conserved L-polymerase motifs.

isolate, the function of these proteins is unlikely to be essential in the basic life cycle of BDV (Pleschka *et al*, 2001).

Motifs are characterized on some BDV proteins, including nuclear localization signals (NLSs) on N (Kobayashi *et al*, 1998; Pyper and Gartner, 1997), P (Schwemmle *et al*, 1999b; Shoya *et al*, 1998), L (Walker and Lipkin, 2002), and presumably X (Wolff *et al*, 2002), as well as a nuclear export sequence (NES) on N (Kobayashi *et al*, 2001) (see Figure 2). Sites of interaction between N, P, and X (Berg *et al*, 1998; Kobayashi *et al*, 2001; Schwemmle *et al*, 1998), and the phosphorylation sites of P (Schwemmle *et al*, 1997) have been mapped. Further, the viral G protein has recently been analyzed in more detail. Nonetheless, the proposed functions of BDV proteins are still hypothetical and based primarily on analogy to other NNS RNA viruses.

The BDV G protein is a type I glycoprotein of 94 kDa (Kiermayer *et al*, 2002; Richt *et al*, 1998; Schneider *et al*, 1997a). Proteolytic processing by the cellular protease furin (Richt *et al*, 1998) yields two fragments, GP-N and GP-C (Kiermayer *et al*, 2002; Richt *et al*, 1998) (Figure 2). The 94-kDa precursor accumulates in the endoplasmic reticulum, whereas the GP-C cleavage product is transferred to the cell

membrane. However, both the glycosylated 94-kDa precursor and glycosylated GP-C (gp43) are found associated with infectious particles (Gonzalez-Dunia *et al*, 1997). The second cleavage product, glycosylated GP-N (gp51), was elusive until recently, when it was shown to be present in infected cells and infectious particles by enzymatic deglycosylation on blot (Kiermayer *et al*, 2002).

BDV enters the host cell by receptor-mediated endocytosis, and membrane fusion occurs in the acidic environment of the endosome (Gonzalez-Dunia *et al*, 1998). Cleavage of the 94-kDa precursor is essential for virus infectivity, and it has been speculated that proteolytic processing might activate a sequence reminiscent of fusion peptides of other viruses located close to the N-terminus of gp43 (Richt *et al*, 1998). Recent analyses by pseudotyping, however, indicate that the N-terminal portion of G alone is sufficient to mediate virus attachment and entry into the cell (Perez *et al*, 2001).

BDV is still the sole known example of the family Bornaviridae. Reported sequences have less than 6% divergence at the nt level, a remarkable degree of conservation for an RNA virus (Kilbourne, 1991; Schneider *et al*, 1994a). The extent to which this represents selective pressure or fidelity of the BDV RNA-dependent RNA polymerase is unclear. Resolution of this question awaits establishment of *in vitro* transcription and/or reverse genetic systems. Interestingly, BDV replication and spread were recently found to be inhibited by Ara-C (1-β-D-arabinofuranosylcytosine), a nucleoside analogue that specifically inhibits DNA polymerase enzymes. The mechanism of action remains unclear, but is postulated to be direct inhibition of the viral polymerase rather than an indirect effect mediated by host cell factors (Bajramovic *et al*, 2002).

Epidemiology

Natural BD has been well known as a fatal behavioral and movement disorder of horses and sheep in endemic areas of Central Europe for more than a century (Ludwig *et al*, 1988). Outbreaks of severe disease are infrequent and remain restricted to this region; however, recent studies suggest a larger host as well as geographic range of BDV infection (Bahmani *et al*, 1996; Caplazi *et al*, 1994; Dauphin *et al*, 2001; Galabru *et al*, 2000; Hagiwara *et al*, 1996, 1997a, 1997b, 2001; Helps *et al*, 2001; Horii *et al*, 2001; Kao *et al*, 1993; Lundgren *et al*, 1993; Malkinson *et al*, 1993; Nakamura *et al*, 1995, 1996; Reeves *et al*, 1998; Yilmaz *et al*, 2002). Enhanced case ascertainment due to surging interest in BDV and the introduction of sensitive serologic and nucleic acid–based diagnostic assays for infection almost certainly contribute to these findings; however, dissemination of the virus has not been excluded comparing archived materials to more recently collected specimens. With a few notable exceptions, including reports of disease in Japan in horses (Hagiwara *et al*, 2000); domestic cats (Nakamura *et al*, 1999); and dogs (Okamoto *et al*, 2002); and in Austria and France in dogs (Weissenbock *et al*, 1998) and lynxes (Degiorgis *et al*, 2000), investigators reporting infection in new regions or host species do not typically pursue studies of virus isolation, experimental infection, or detailed neuropathology. This is unfortunate as the credibility of BDV epidemiology would be enhanced by more comprehensive analyses.

Neither the reservoir nor the mode for transmission of natural infection is known. An olfactory route for transmission has been proposed because intranasal infection is efficient and the olfactory bulbs of naturally infected horses show inflammation and edema early in the course of disease (Ludwig *et al*, 1988). Reports of BDV nucleic acid and proteins in peripheral blood mononuclear cells also indicate the possibility of hematogenous transmission (Rubin *et al*, 1995; Sierra-Honigmann *et al*, 1993). There is one report suggesting potential for vertical transmission (Hagiwara *et al*, 2000). Rodents are proposed as a candidate for BDV reservoirs because experimental infection of neonatal rats results in virus persistence and is associated with the presence of virus in saliva, urine, and feces (Sierra-Honigmann *et al*, 1993). The one reported study examining natural infection of wild rodents has not supported this hypothesis (Tsujimura *et al*, 1999). BDV has been reported in bird excrement, suggesting the possibility of an avian reservoir (Berg *et al*, 2001). Rigorous epidemiologic investigation of the global distribution and ecology of BDV should be emphasized in future research.

Sequence conservation amongst isolates is a major confounding factor in BDV epidemiology. Infection is frequently diagnosed by detecting BDV transcripts in clinical materials such as peripheral blood mononuclear cells or tissues following amplification by nested reverse transcriptase–polymerase chain reaction (nRT-PCR). This method, although sensitive, is prone to artifact due to inadvertent introduction of template from laboratory isolates or cross contamination of samples (Schwemmle *et al*, 1999a). In most viral systems, specific signatures readily facilitate determination of provenance; however, in BDV, similarities in sequence between putative new isolates and confirmed isolates cannot be used to exclude the former as artifacts.

Unique sequence variations specific for a particular host species, time point of isolation, or geographic origin are not yet defined (Binz *et al*, 1994; Schneider *et al*, 1994a; Zimmermann *et al*, 1994). One isolate from a horse in Austria was found to have a higher level of divergence at the nt level than others (strain No/98; Nowotny *et al*, 2000; Pleschka *et al*, 2001). Protein sequence was highly conserved (93% to 96% over the entire genome). Biological characterization of this isolate is pending; it remains to be determined whether phenotypic features warrant

classification of this isolate as a new strain of BDV. Laboratory isolates may differ in virulence in animal models depending on their passage history (Hirano *et al*, 1983; Kao *et al*, 1984); however, the first evidence to indicate a molecular basis for such differences was reported only recently when enhanced neurovirulence was associated with two amino acid changes each in the G protein and the polymerase genes (Nishino *et al*, 2002). Another phenotypic difference, sensitivity to amantadine sulfate, is reported for some human isolates (Bode *et al*, 1997; Dietrich *et al*, 2000; Ferszt *et al*, 1999). Other isolates appear to be resistant to amantadine sulfate *in vitro* and *in vivo* (Cubitt and de la Torre, 1997; Hallensleben *et al*, 1997; Stitz *et al*, 1998b). It is unclear whether sensitivity to this drug is specific to the isolates studied by Bode and coworkers. The authors are not aware of similar data for other human isolates (Nakamura *et al*, 2000; Planz *et al*, 1999). The epidemiology of human disease is unresolved (Tables 1 and 2) (Bode *et al*, 2001; Lipkin *et al*, 2001; Schwemmle, 2001). Reports of international collaborative studies based on standardized diagnostic instruments and molecular and serological assays are anticipated in 2003.

Animal and tissue culture models of pathogenesis

Once inside the host cell, mechanisms for BDV pathogenicity remain poorly defined. Virus infection is noncytopathic and persistent. Mechanisms of pathogenicity in the brain may include direct interaction with intracellular signaling and function, or interference with intercellular communication essential to brain function, probably through soluble factors such as cytokines, neurotrophins, and/or neurotransmitters (Gosztonyi and Ludwig, 2001; Hornig *et al*, 2001). The best studied systems are the adult- and the neonatally-infected Lewis rat models.

Infection of adult Lewis rats produces a prominent neurobehavioral disorder and is characterized by pronounced immunopathology. In the acute phase (4 to 8 weeks post infection), cellular infiltrates ($CD4^+$ and $CD8^+$ T cells, natural killer [NK] cells, macrophages) and Th_1-type cytokines are prominent in perivascular and parenchymal regions of the central nervous system (CNS); in the chronic phase (15 weeks post infection and beyond), a decline in infiltrates is accompanied by an increase in Th_2-type cytokines and a shift to a humoral immune response (Hatalski *et al*, 1998). $CD8^+$ T cells mediate destruction of virus-infected cells in the CNS, whereas $CD4^+$ T cells promote production of antiviral antibodies. Although antibodies to N and P generated during the acute phase of disease are non-neutralizing (Furrer *et al*, 2001), antibodies with neutralizing capacity increase dramatically after the acute phase (Hatalski *et al*, 1995) and likely participate in restriction of virus to neural tissues (Stitz *et al*, 1998a). Mechanisms contributing to viral persistence are as yet uncertain. Altered viral gene expression is an unlikely explanation as there is little substantive change in the CNS over the course of disease in viral titers (Carbone *et al*, 1987; Narayan *et al*, 1983), transcripts coding for BDV proteins, or levels of BDV N and P proteins (Hatalski, 1996). Modulation of immune responses as BD progresses to the chronic phase may exert some influence on BDV persistence. BDV-specific Th_1 tolerance appears to be induced; as rats progress to the chronic stage of infection, the capacity of lymphocytes isolated from acute phase CNS to lyse BDV-specific target cells is lost (Sobbe *et al*, 1997). These changes in BDV-specific tolerance during chronic infection may result from presentation of BDV antigens in brain without essential costimulatory signals (Karpas *et al*, 1994; Khoury *et al*, 1995; Schwartz, 1992), allowing Th_1 cells to become anergic or undergo apoptosis. Indeed, apoptosis of perivascular inflammatory cells is most apparent at 5-6 weeks post infection, coincident with the onset of the chronic phase and the decline in encephalitis (Hatalski *et al*, 1997).

The distinct clinical and behavioral features of the immune-mediated adult rat model closely parallel the CNS pathology of the acute and chronic phases. In the acute phase, coinciding with monocyte infiltration in CNS regions of early viral burden, such as hippocampus, amygdala, and other limbic structures (Carbone *et al*, 1987), animals demonstrate exaggerated startle responses and hyperactivity. As animals enter the chronic phase of infection, high-grade stereotyped motor behaviors (continuous repetition of behavioral elements, including sniffing, chewing, scratching, grooming, and self-biting), dyskinesias, dystonias, and flexed seated postures appear (Solbrig *et al*, 1994), in parallel with the spread of virus throughout limbic and prefrontal circuits. Up to 10% of animals become obese, achieving body weights up to 300% of normal (Ludwig *et al*, 1988).

Disorders of movement and behavior in adult-infected rats are associated with dysfunction in dopamine (DA) circuits (Solbrig *et al*, 1994, 1995, 1996a, 1996b, 1998), as seen in many neuropsychiatric disorders (Anderson, 1994; Cooper *et al*, 1991; Ernst *et al*, 1997; Hamner and Diamond, 1996; Kane and Marder, 1993; Kelsoe *et al*, 1996; Partonen, 1996), and may be further linked to serotonin (5HT) abnormalities (Solbrig *et al*, 1995). Enhanced sensitivity of central DA systems of adult-infected BD animals to DA agonists, antagonists, and DA reuptake inhibitors is observed. Administration of the mixed-acting DA agonist, dextroamphetamine (Solbrig *et al*, 1994), or of cocaine, a DA reuptake inhibitor, to adult-infected rats elicits increased locomotor and stereotypic behavior, indicating dose-dependent potentiation of DA neurotransmission (Solbrig *et al*, 1998). Low, presynaptic, autoreceptor doses of the direct DA agonist, apomorphine, reduce hyperactivity, whereas

Table 1 Serum immunoreactivity to BDV in subjects with various diseases

Disease	*Prevalence*		*Assay*	Reference
	Disease	*Control*		
Psychiatric (various)	0.6% (4/694)	0% (0/200)	IFA	Rott *et al*, 1985
	2% (13/642)	2% (11/540)	IFA	Bode *et al*, 1988
	4%–7% (200/5000–350/5000)	1% (10/1000)	WB/IFA	Rott *et al*, 1991
	12% (6/49)		IFA	Bode *et al*, 1993
	30% (18/60)		WB	Kishi *et al*, 1995b
	14% (18/132)	1.5% (3/203)	WB	Sauder *et al*, 1996
	24% (13/55)	11% (4/36)	IFA	Igata-Yi *et al*, 1996
	0% (0/44)	0% (0/70)	IFA/WB	Kubo *et al*, 1997
	2.8% (35/1260)	1.1% (10/917	ECLIA	Yamaguchi *et al*, 1999
	9.8% (4/41)		IFA	Bachmann *et al*, 1999
	14.8% (4/27)	0% (0/13)	IFA	Vahlenkamp *et al*, 2000
	0% (0/89)	0% (0/210)	IFA/WB	Tsuji *et al*, 2000
	1.1%–5.5% (1/90 or 5/90)	0% (0/45)	WB (N or P)	Fukuda *et al*, 2001
	2.1% (17/816)		ECLIA	Rybakowski *et al*, 2001a
	2.4% (23/946)	1.0% (4/412)	ECLIA	Rybakowski *et al*, 2001b, 2002
	12.6% (11/87)	15.5% (45/290)	IFA	Lebain *et al*, 2002
Affective disorders	4.5% (12/265)	0% (0/105)	IFA	Amsterdam *et al*, 1985
	4% (12/285)	0% (0/200)	IFA	Rott *et al*, 1985
	38% or 12% (53/138 or 17/138)	16% or 4% (19/117 or 5/117)	WB (N or P)	Fu *et al*, 1993a
	37% (10/27)		IFA	Bode *et al*, 1993
	12% (6/52)	1.5% (3/203)	WB	Sauder *et al*, 1996
	0%–0.8% (0/122–1/122)	0% (0/70)	IFA/WB	Kubo *et al*, 1997
	2% (1/45)	0% (0/45)	WB	Fukuda *et al*, 2001
	92.6% (26/28)	32.3% (21/65)	CIC	Bode *et al*, 2001
Schizophrenia	25% (1/4)		IFA	Bode *et al*, 1993
	9%–28% (8/90 or 25/90)	0%–20% (0/20 or 4/20)	WB (N or P)	Waltrip *et al*, 1995
	17% (15/90)	15% (3/20)	IFA	Waltrip *et al*, 1995
	14% (16/114)	1.5% (3/203)	WB	Sauder *et al*, 1996
	20% (2/10)		WB	Richt *et al*, 1997
	0%–1% (0/167–2/167)	0% (0/70)	IFA/WB	Kubo *et al*, 1997
	14% (9/64)	0% (0/20)	WB	Waltrip *et al*, 1997
	17.9% or 35.8% (12/67 or 24/67)	0% (0/26)	WB (N or P)	Iwahashi *et al*, 1997
	12.1% (38/276)		WB	Chen *et al*, 1999b
	10.3% (3/29)	23.1% (6/26)	IFA	Selten *et al*, 2000
	9% (4/45)	0% (0/45)	WB	Fukuda *et al*, 2001
	12.6% (11/87)	15.5% (45/290)	IFA	Lebain *et al*, 2002
CFS	24% (6/25)		WB	Nakaya *et al*, 1996
	34% (30/89)		WB	Kitani *et al*, 1996; Nakaya *et al*, 1997
	0% (0/69)	0% (0/62)	WB	Evengard *et al*, 1999
	100% (7/7)	33% (1/3)	WB	Nakaya *et al*, 1999
MS	13% (15/114)	2.3% (11/483)	IP/IFA	Bode *et al*, 1992
	0% (0/50)		IFA	Kitze *et al*, 1996
Mental health care workers	9.8% (8/82)	2.9% (8/277)	WB	Chen *et al*, 1999b
Family of schizophrenic patients	12.1% (16/132)	2.9% (8/277)	WB	Chen *et al*, 1999b
Live near horse farms	2.6%–14.8% (2/78—16/108)	1% (1/100)	ELISA	Takahashi *et al*, 1997
Ostrich exposure	46% (19/41)	10% (4/41)	ELISA	Weisman *et al*, 1994

Abbreviations: ELISA, enzyme-linked immunosorbent assay; IFA, immunofluorescence assay; WB, Western immunoblot; IP, immunoprecipitation; CIC, circulating immune complexes; CFS, chronic fatigue syndrome; MS, multiple sclerosis; N, nucleoprotein; P, phosphoprotein.

higher doses increase locomotion. Both pre- and postsynaptic sites of the DA transmitter system appear to be damaged in striatum: DA reuptake sites, as measured by mazindol binding, are reduced in caudate-putamen (Solbrig *et al*, 1998) and nucleus accumbens (Solbrig *et al*, 1996b); and postsynaptic D2, but not D1, receptor binding is markedly reduced in caudate-putamen whereas D2 and D3 receptor binding are reduced in nucleus accumbens (Solbrig *et al*, 1994, 1996a, 1996b). In contrast, postsynaptic DA receptors (D1, D2) remain intact in prefrontal cortex (Solbrig *et al*, 1996a). Further support for D2-selective losses and resultant D1 hypersensitivity as mediators of neurobehavioral disturbances in adult BD is found in the ability to reverse locomotor hyperactivity through administration of D1 receptor–blocking agents, such as the D1 antagonist, SCH23390, or clozapine, an atypical antipsychotic with mixed D1,

Table 2 BDV RNA, virus or protein in subjects with various diseases

		Prevalence			
Disease	*Tissue*	*Disease*	*Controls*	*Divergence**	*Reference*
Psychiatric (various)	PBMC	67% (4/6)	0% (0/10)	0%–3.6%	Bode *et al*, 1995
	PBMC	37% (22/60)			Kishi *et al*, 1995b
	PBMC	42% (5/12)	0% (0/23)	0%–4.0%	Sauder *et al*, 1996
	PBMC-coculture	9% (3/33)	0% (0/5)	0.07%–0.83%	Bode *et al*, 1996; de la Torre *et al*, 1996
	PBMC	2% (2/106)	0% (0/12)		Kubo *et al*, 1997
	PBMC	0% (0/24)	0% (0/4)		Richt *et al*, 1997
	PBMC	0% (0/159)			Lieb *et al*, 1997
	Blood	(1/1)			Planz *et al*, 1998
	PBMC	4% (5/126)	2.4% (2/84)		Iwata *et al*, 1998
	PBMC	20% (3/15)	0% (0/3)		Planz *et al*, 1999
	PBMC	0% (0/81)			Kim *et al*, 1999
	PBMC	0% (0/27)			Bachmann *et al*, 1999
	CSF	0% (0/27)			Bachmann *et al*, 1999
	PBMC	1.8% (1/56)	0.6% (1/173)		Tsuji *et al*, 2000
	PBMC	37% (10/27)	15.4% (2/13)		Vahlenkamp *et al*, 2000
	PBMC	1.1% (1/90)	0% (0/45)		Fukuda *et al*, 2001
Affective disorders	PBMC	33% (1/3)	0% (0/23)		Sauder *et al*, 1996
	PBMC	17% (1/6)	0% (0/36)		Igata-Yi *et al*, 1996
	Brain	40% (2/5)	0% (0/10)		Salvatore *et al*, 1997
	PBMC	4% (2/49)	2% (2/84)	0%–5.1%	Iwata *et al*, 1998
	CSF	5% (3/65)	0% (0/69)	[Protein]	Deuschle *et al*, 1998
	PBMC	2% (1/45)	0% (0/45)		Fukuda *et al*, 2001
Schizophrenia	Brain	0% (0/3)	0% (0/3)		Sierra-Honigmann *et al*, 1995
	CSF	0% (0/8)	0% (0/8)		Sierra-Honigmann *et al*, 1995
	PBMC	0% (0/7)	0% (0/7)		Sierra-Honigmann *et al*, 1995
	PBMC	64% (7/11)	0% (0/23)		Sauder *et al*, 1996
	PBMC	10% (5/49)	0% (0/36)		Igata-Yi *et al*, 1996
	PBMC	100% (3/3)		4.2%–9.3%	Kishi *et al*, 1996
	PBMC	0% (0/10)	0% (0/10)		Richt *et al*, 1997
	Brain	53% (9/17)	0% (0/10)		Salvatore *et al*, 1997
	PBMC	9.8% (6/61)	0% (0/26)		Iwahashi *et al*, 1997
	PBMC	4% (3/77)	2% (2/84)	0%–5.1%	Iwata *et al*, 1998
	PBMC	14% (10/74)	1.4% (1/69)		Chen *et al*, 1999a
	Brain	25% (1/4)		[RNA, virus, protein]	Nakamura *et al*, 2000
	PBMC	13.8% (4/29)	34.6% (9/26)		Selten *et al*, 2000
	PBMC	0% (0/45)	0% (0/45)		Fukuda *et al*, 2001
	PBMC	12% (3/25)		6.0%–14%	Nakaya *et al*, 1996
	PBMC	12% (7/57)	4.9% (8/172)		Kitani *et al*, 1996; Nakaya *et al*, 1997
	PBMC	0% (0/18)			Evengard *et al*, 1999
FMS	CSF	0% (0/18)	0% (0/6)		Wittrup *et al*, 2000
Hippocampal sclerosis	Brain	80% (4/5)			de la Torre *et al*, 1996
	Brain	15% (3/20)	0% (0/85)		Czygan *et al*, 1999
MS	CSF	11% (2/19)	0% (0/69)	[Protein]	Deuschle *et al*, 1998
	PBMC	0% (0/34)	0% (0/40)		Haase *et al*, 2001
Mental health care workers	PBMC	15% (7/45)	1.4% (1/69)		Chen *et al*, 1999a
Normal controls	PBMC		5% (8/172)		Kishi *et al*, 1995a
	Brain		6.7% (2/30)		Haga *et al*, 1997

Abbreviations: PBMC, peripheral blood mononuclear cells; CSF, cerebrospinal fluid; CFS, chronic fatigue syndrome; FMS, fibromyalgia syndrome. *Divergence of P-gene nucleotide sequence from common BDV isolates (strain V and He/80).

D2, D3, and D4 antagonist activity, but not through the administration of D2-selective antagonists (e.g., raclopride) (Solbrig *et al*, 1994).

Neurochemical studies further support a lesion in DA transmission consistent with partial DA deafferentation and compensatory metabolic hyperactivity in nigrostriatal and mesolimbic DA systems. Decreases in DA levels exceed those in dihydroxyphenylacetic acid (DOPAC, the major metabolite of DA) levels in high-performance liquid chromatography (HPLC) analysis of tissues from striatum, nucleus accumbens, and olfactory tubercle (Solbrig *et al*, 1994), whereas in prefrontal cortex marked increases are noted in DOPAC (Solbrig *et al*, 1996a). Depletion of tyrosine hydroxylase (TH)-immunoreactive cells in substantia nigra and ventral tegmental area (Solbrig *et al*, 1994) and in striatum (Solbrig *et al*, 2000), and a decrease in TH protein content in striatum but not in substantia nigra pars compacta, are nonetheless accompanied by an increase in TH functional activity (Solbrig *et al*, 2000). Increased gene expression of neurotrophic factors that

support growth of DA-producing cells *in vitro*, including brain-derived neurotrophic factor (BDNF), neurotrophin (NT)-3, NT-4, and ciliary neurotrophic factor (CNTF), may also contribute to the sensitivity to DA agonist action in adult BD (Solbrig *et al*, 2000).

Additional neuromodulator abnormalities are also noted in the adult model. The expression of genes for neuromodulatory substances and their associated synthesizing enzymes, including somatostatin, cholecystokinin, and glutamic acid decarboxylase, is greatly reduced during the acute phase and recovers toward normal in the chronic phase of adult BD (Lipkin *et al*, 1988). The cholinergic system, a major participant in sensorimotor processing, learning, and memory, is similarly affected, with a decrease in choline acetyltransferase-positive fibers as early as day 6 post infection, progressing to nearly complete loss of these fibers in hippocampus and neocortex by day 15 (Gies *et al*, 1998). Preliminary work on dysregulation of 5HT and norepinephrine (NE) systems suggests metabolic hyperactivity of 5HT, with a modest increase in the metabolite 5-hydroxyindoleacetic acid in striatum, and of NE, as evidenced by a small increase in the NE metabolite, 3-methoxy-4-hydroxyphenethyleneglycol, in prefrontal and anterior cingulate cortex regions (Solbrig *et al*, 1995). These changes may reflect compensatory upregulation or heterotypic sprouting following partial loss of DA afferents to these brain regions. Selective effects of BDV on 5HT and NE pre- or postsynaptic receptors have not yet been investigated. Pharmacologic and neurotransmitter-specific molecular probes have also been used to characterize endogenous opioid systems in the adult rat model. Infected animals respond abnormally to the opiate antagonist, naloxone, with hyperkinesis and seizures, and also demonstrate increases in striatal preproenkephalin mRNA at 14 and 21 days (Fu *et al*, 1993b), and 6 weeks after BDV infection (Solbrig *et al*, 2002). BDV and met-enkephalin immunoreactivity also coincided in a high percentage of cells (Solbrig *et al*, 2002). Induction of the enkephalin system in adult BD may relate to increased levels of phosphorylated cyclic AMP response element binding (phosphoCREB) protein through activation by BDV of the mitogen-activated protein (MAP) kinase pathway, thus stimulating transcription factors that regulate enkephalin expression in striatum (Konradi *et al*, 1993). However, the mechanisms by which these changes in endogenous opioid systems occur are unclear. The marked CNS inflammation in adult-infected rats confounds the role of direct effects of the virus, virus effects on resident cells of the CNS, and cellular immune responses to viral gene products in production of monoamine, cholinergic, and opiatergic dysfunction in BD. Thus, our efforts have turned towards the neonatal rat model in an effort to identify the functional and structural consequences of BDV in a system that is linked to more direct interactions of the virus with CNS.

The neonatal rat model does not show overt immunopathology; instead, despite high virus load in the brain and lifelong persistence, animals infected within the first 12 h of life develop a mild behavioral syndrome and restricted neuropathology that may provide a more intriguing model for neuropsychiatric disorders. The cerebellar and hippocampal dysgenesis observed in neonatally infected animals is consistent with the more subtle neurodevelopmental abnormalities reported by some investigators in autism (Kemper and Bauman, 1993), schizophrenia (Altshuler *et al*, 1987; Fish *et al*, 1992), and affective disorders (Soares and Mann, 1997). Neonatally infected animals display a wide range of physiologic and neurobehavioral disturbances. They are smaller than uninfected littermates (Bautista *et al*, 1994; Carbone *et al*, 1991b), without demonstrable alteration of glucose, growth hormone, or insulin-like growth factor-1 (Bautista *et al*, 1994) or amount of food ingested (Bautista *et al*, 1995); display an enhanced preference for salt solutions; and exhibit altered circadian rhythms (Bautista *et al*, 1994). Behavioral and cognitive changes in rats infected in the neonatal period include abnormal early locomotor development (Hornig *et al*, 1999), spatial and aversive learning deficits (Dittrich *et al*, 1989; Rubin *et al*, 1999), increased motor activity (Bautista *et al*, 1994; Hornig *et al*, 1999), abnormal anxiety responses (Dittrich *et al*, 1989; Hornig *et al*, 1999; Pletnikov *et al*, 1999a), stereotypic behaviors (Hornig *et al*, 1999), and reduced initiation of and response to nondominance-related play interactions (Pletnikov *et al*, 1999b). Thus, the neuropathologic, physiologic, and neurobehavioral features of BDV infection of neonates indicate that it not only provides a useful model for exploring the mechanisms by which viral and immune factors may damage developing neurocircuitry, but also has significant links to the range of biologic, neurostructural, locomotor, cognitive, and social deficits observed in a wide range of human neuropsychiatric illnesses, including the neurodevelopmental disorder, autism.

CNS dysfunction in neonatally infected animals has been proposed to be linked to direct viral effects on morphogenesis of the hippocampus and cerebellum, two structures in rodents that continue to mature postnatally. Although overall architecture is maintained, granule cells of dentate gyrus (Carbone *et al*, 1991b; Hornig *et al*, 1999; Rubin *et al*, 1999) and Purkinje cells of cerebellum (Eisenman *et al*, 1999; Hornig *et al*, 1999) are lost through apoptosis (Hornig *et al*, 1999). The extent of neuronal loss in dentate gyrus is correlated with the severity of spatial learning and memory deficiencies in neonatally-infected Lewis rats (Rubin *et al*, 1999). Subtle testing of cerebellar function demonstrates deficits in motor coordination and postural stability (Hornig *et al*, 1999; Pletnikov *et al*, 2001), consistent with Purkinje cell losses. Further studies are needed to evaluate the mechanisms by which early postnatal exposure to

BDV induces apoptotic losses and functional damage in cerebellar and limbic circuitry.

Although cellular inflammatory response to BDV following neonatal infection is restricted, a phenomenon ascribed to the immaturity of rat postnatal immune function, a brief surge in mononuclear cell infiltrates occurs (Hornig *et al*, 1999; Sauder and de la Torre, 1999), along with elevations in expression of proinflammatory cytokine (Hornig *et al*, 1999; Sauder and de la Torre, 1999), chemokine (Sauder *et al*, 2000), and chemokine receptor (Rauer *et al*, 2002) transcripts. However, this transient immune response does not colocalize with sites of neuropathologic damage (Weissenböck *et al*, 2000). Neuropathology instead parallels regions and timecourse of microglial proliferation and expression of major histocompatibility complex (MHC) class I and class II, intercellular adhesion molecule (ICAM), CD4 and CD8 molecules (Weissenböck *et al*, 2000). Humoral immune response to BDV in neonatally infected animals is also curtailed, with anti-BDV antibody titers remaining below 1:10 through 133 days post infection (Carbone *et al*, 1991b).

Although reduced levels of neurotrophic factor mRNAs occur in the neonatal model (Hornig *et al*, 1999; Zocher *et al*, 2000), these changes are restricted to hippocampus and are unlikely to account for losses of Purkinje cells in cerebellum. Alternatively, it is conceivable that abnormal regulation of apoptosis, either failure of normal apoptotic sequences to be curtailed with age or excess activation of apoptotic cell programs, may contribute to abnormal CNS architecture in neonatal infections with BDV or other neurotropic viruses. Excitotoxic stimulation, including activation of glutamatergic circuitry, is one factor that might trigger neuronal apoptosis. Complex alterations in mRNAs for apoptosis mediators, including increased levels of mRNAs for Fas (CD95) and interleukin-1 converting enzyme (ICE, caspase-1), two promotors of apoptosis, and decreased mRNA for bcl-x, a factor that inhibits apoptosis, have been identified in hippocampus, amygdala, prefrontal cortex, nucleus accumbens, and cerebellum, and are consistent with promotion of apoptosis throughout the brains of rats neonatally infected with BDV (Hornig *et al*, 1999).

Effects of BDV infection at the cellular level are only beginning to be unveiled. Inhibition of cell-to-cell spread of BDV by a MAP kinase/extracellular signal-regulated kinase (ERK) kinase (MEK) inhibitor in cell culture (Planz *et al*, 2001) and analyses of neuronal differentiation of PC12 cells (Hans *et al*, 2001) indicate an interaction of BDV with cellular MAP kinase signaling pathways. Infected PC12 cells demonstrate constitutive phosphorylation of MEK, ERK, and the transcriptional activator, Elk-1 (Hans *et al*, 2001), but fail to differentiate with nerve growth factor (NGF) treatment. Inhibition of neurite outgrowth is also reported in other infected cell lines (Kamitani *et al*, 2001), and has been ascribed to interference by P protein with the normal interaction between the neurite outgrowth factor, amphoterin, and its receptor, RAGE (*R*eceptor for *A*dvanced *G*lycation *E*nd-products). BDV-infected cells have altered intracellular distribution of amphoterin, with reduced levels of amphoterin, and of RAGE activation at growth cones of extending cells (Kamitani *et al*, 2001).

Summary

BDV continues to be a fertile system for investigators representing a variety of disciplines. What began for many of us as a tantalizing, if simplistic, potential explanation for the pathogenesis of mental illness has instead become a tool for cellular biology, immunology, and developmental neurobiology.

References

Altshuler LL, Conrad A, Kovelman JA, Scheibel A (1987). Hippocampal pyramidal cell orientation in schizophrenia: a controlled neurohistologic study of the Yakovlev Collection. *Arch Gen Psychiatry* **44:** 1094–1098.

Amsterdam J, Winokur A, Dyson W, Herzog S, Gonzalez F, Rott R, Koprowski H (1985). Borna disease virus: a possible etiologic factor in human affective disorders. *Arch Gen Psychiatry* **42:** 1093–1096.

Anderson GM (1994). Studies on the neurochemistry of autism. In: *The neurobiology of autism*. Bauman ML, Kemper TL (eds). Baltimore: Johns Hopkins University Press, pp 227–242.

Bachmann S, Caplazi P, Fischer M, Ehrensperger F, Cone RW (1999). Lack of association between Borna disease virus infection and neurological disorders among HIV-infected individuals. *J NeuroVirol* **5:** 190–195.

Bahmani MK, Nowrouzian I, Nakaya T, Nakamura Y, Hagiwara K, Takahashi H, Rad MA, Ikuta K (1996). Varied prevalence of Borna disease virus infection in Arabic, thoroughbred and their cross-bred horses in Iran. *Virus Res* **45:** 1–13.

Bajramovic JJ, Syan S, Brahic M, de la Torre JC, Gonzalez-Dunia D (2002). 1-beta-D-Arabinofuranosylcytosine inhibits borna disease virus replication and spread. *J Virol* **76:** 6268–6276.

Bautista JR, Rubin SA, Moran TH, Schwartz GJ, Carbone KM (1995). Developmental injury to the cerebellum following perinatal Borna disease virus infection. *Brain Res Dev Brain Res* **90:** 45–53.

Bautista JR, Schwartz GJ, de la Torre JC, Moran TH, Carbone KM (1994). Early and persistent abnormalities in rats with neonatally acquired Borna disease virus infection. *Brain Res Bull* **34:** 31–40.

Berg M, Ehrenborg C, Blomberg J, Pipkorn R, Berg AL (1998). Two domains of the Borna disease virus p40 protein are required for interaction with the p23 protein. *J Gen Virol* **79:** 2957–2963.

Berg M, Johansson M, Montell H, Berg AL (2001). Wild birds as a possible natural reservoir of Borna disease virus. *Epidemiol Infect* **127:** 173–178.

Binz T, Lebelt J, Niemann H, Hagenau K (1994). Sequence analyses of the p24 gene of Borna disease virus in naturally infected horse, donkey and sheep. *Virus Res* **34:** 281–289.

Bode L, Dietrich DE, Stoyloff R, Emrich HM, Ludwig H (1997). Amantadine and human Borna disease virus in vitro and in vivo in an infected patient with bipolar depression [letter] [see comments]. *Lancet* **349:** 178–179.

Bode L, Dürrwald R, Rantam FA, Ferszt R, Ludwig H (1996). First isolates of infectious human Borna disease virus from patients with mood disorders. *Mol Psychiatry* **1:** 200–212.

Bode L, Ferszt R, Czech G (1993). Borna disease virus infection and affective disorders in man. *Arch Virol Suppl* **7:** 159–167.

Bode L, Reckwald P, Severus WE, Stoyloff R, Ferszt R, Dietrich DE, Ludwig H (2001). Borna disease virus-specific circulating immune complexes, antigenemia, and free antibodies—the key marker triplet determining infection and prevailing in severe mood disorders. *Mol Psychiatry* **6:** 481–491.

Bode L, Riegel S, Lange W, Ludwig H (1992). Human infections with Borna disease virus: seroprevalence in patients with chronic diseases and healthy individuals. *J Med Virol* **36:** 309–315.

Bode L, Riegel S, Ludwig H, Amsterdam JD, Lange W, Koprowski H (1988). Borna disease virus-specific antibodies in patients with HIV infection and with mental disorders [letter]. *Lancet* **2:** 689.

Bode L, Zimmermann W, Ferszt R, Steinbach F, Ludwig H (1995). Borna disease virus genome transcribed and expressed in psychiatric patients. *Nat Med* **1:** 232–236.

Briese T, de la Torre JC, Lewis A, Ludwig H, Lipkin WI (1992). Borna disease virus, a negative-strand RNA virus, transcribes in the nucleus of infected cells. *Proc Natl Acad Sci U S A* **89:** 11486–11489.

Briese T, Schneemann A, Lewis AJ, Park YS, Kim S, Ludwig H, Lipkin WI (1994). Genomic organization of Borna disease virus. *Proc Natl Acad Sci U S A* **91:** 4362–4366.

Caplazi P, Waldvogel A, Stitz L, Braun U, Ehrensperger F (1994). Borna disease in naturally infected cattle. *J Comp Pathal* **111:** 62–72.

Carbone KM, Duchala CS, Griffin JW, Kincaid AL, Narayan O (1987). Pathogenesis of Borna disease in rats: evidence that intra-axonal spread is the major route for virus dissemination and the determinant for disease incubation. *J Virol* **61:** 3431–3440.

Carbone KM, Moench TR, Lipkin WI (1991a). Borna disease virus replicates in astrocytes, Schwann cells and ependymal cells in persistently infected rats: location of viral genomic and messenger RNAs by in situ hybridization. *J Neuropathol Exp Neurol* **50:** 205–214.

Carbone KM, Park SW, Rubin SA, Waltrip RW 2nd, Vogelsang GB (1991b). Borna disease: association with a maturation defect in the cellular immune response. *J Virol* **65:** 6154–6164.

Chen CH, Chiu YL, Shaw CK, Tsai MT, Hwang AL, Hsiao KJ (1999a). Detection of Borna disease virus RNA from peripheral blood cells in schizophrenic patients and mental health workers. *Mol Psychiatry* **4:** 566–571.

Chen CH, Chiu YL, Wei FC, Koong FJ, Liu HC, Shaw CK, Hwu HG, Hsiao KJ (1999b). High seroprevalence of Borna virus infection in schizophrenic patients, family members and mental health workers in Taiwan [In Process Citation]. *Mol Psychiatry* **4:** 33–38.

Cooper JR, Bloom FE, Roth RH (1991). *The biochemical basis of neuropharmacology.* New York: Oxford University Press.

Cubitt B, de la Torre JC (1994). Borna disease virus (BDV), a nonsegmented RNA virus, replicates in the nuclei of infected cells where infectious BDV ribonucleoproteins are present. *J Virol* **68:** 1371–1381.

Cubitt B, de la Torre JC (1997). Amantadine does not have antiviral activity against Borna disease virus. *Arch Virol* **142:** 2035–2042.

Cubitt B, Ly C, de la Torre JC (2001). Identification and characterization of a new intron in Borna disease virus. *J Gen Virol* **82:** 641–646.

Cubitt B, Oldstone C, Valcarcel J, Carlos de la Torre J (1994). RNA splicing contributes to the generation of mature mRNAs of Borna disease virus, a non-segmented negative strand RNA virus. *Virus Res* **34:** 69–79.

Czygan M, Hallensleben W, Hofer M, Pollak S, Sauder C, Bilzer T, Blumcke I, Riederer P, Bogerts B, Falkai P, Schwarz MJ, Masliah E, Staeheli P, Hufert FT, Lieb K (1999). Borna disease virus in human brains with a rare form of hippocampal degeneration but not in brains of patients with common neuropsychiatric disorders. *J Infect Dis* **180:** 1695–1699.

Dauphin G, Legay V, Sailleau C, Smondack S, Hammoumi S, Zientara S (2001). Evidence of Borna disease virus genome detection in French domestic animals and in foxes (Vulpes vulpes). *J Gen Virol* **82:** 2199–2204.

de la Torre JC, Bode L, Durrwald R, Cubitt B, Ludwig H (1996). Sequence characterization of human Borna disease virus. *Virus Res* **44:** 33–44.

Degiorgis MP, Berg AL, Hard Af Segerstad C, Morner T, Johansson M, Berg M (2000). Borna disease in a free-ranging lynx (Lynx lynx). *J Clin Microbiol* **38:** 3087–3091.

Deuschle M, Bode L, Heuser I, Schmider J, Ludwig H (1998). Borna disease virus proteins in cerebrospinal fluid of patients with recurrent depression and multiple sclerosis [letter]. *Lancet* **352:** 1828–1829.

Dietrich DE, Bode L, Spannhuth CW, Lau T, Huber TJ, Brodhun B, Ludwig H, Emrich HM (2000). Amantadine in depressive patients with Borna disease virus (BDV) infection: an open trial. *Bipolar Disord* **2:** 65–70.

Dittrich W, Bode L, Ludwig H, Kao M, Schneider K (1989). Learning deficiencies in Borna disease virus-infected but clinically healthy rats. *Biol Psychiatry* **26:** 818–828.

Eisenman LM, Brother R, Tran MH, Kean RB, Dickson GM, Dietzschold B, Hooper DC (1999). Neonatal Borna disease virus infection in the rat causes a loss of Purkinje cells in the cerebellum. *J NeuroVirol* **5:** 181–189.

Ernst M, Zametkin AJ, Matochik JA, Pascualvaca D, Cohen RM (1997). Low medial prefrontal dopaminergic activity in autistic children. *Lancet* **350:** 638.

Evengard B, Briese T, Lindh G, Lee S, Lipkin WI (1999). Absence of evidence of Borna disease virus infection in Swedish patients with chronic fatigue syndrome. *J NeuroVirol* **5:** 495–499.

Ferszt R, Kuhl KP, Bode L, Severus EW, Winzer B, Berghofer A, Beelitz G, Brodhun B, Muller-Oerlinghausen B, Ludwig H (1999). Amantadine revisited: an open trial of amantadinesulfate treatment in chronically depressed patients with Borna disease virus infection. *Pharmacopsychiatry* **32:** 142–147.

Fish B, Marcus J, Hans SL, Auerbach JG, Perdue S (1992). Infants at risk for schizophrenia: sequelae of a genetic neurointegrative defect: a review and replication analysis of pandysmaturation in the Jerusalem Infant Development Study. *Arch Gen Psychiatry* **49:** 221–235.

Fu ZF, Amsterdam JD, Kao M, Shankar V, Koprowski H, Dietzschold B (1993a). Detection of Borna disease virus-reactive antibodies from patients with affective disorders by western immunoblot technique. *J Affect Disorders* **27:** 61–68.

Fu ZF, Weihe E, Zheng YM, Schafer MK, Sheng H, Corisdeo S, Rauscher FJI, Koprowski H, Dietzschold B (1993b). Differential effects of rabies and borna disease viruses on immediate-, early-, and late-response gene expression in brain tissues. *J Virol* **67:** 6674–6681.

Fukuda K, Takahashi K, Iwata Y, Mori N, Gonda K, Ogawa T, Osonoe K, Sato M, Ogata S, Horimoto T, Sawada T, Tashiro M, Yamaguchi K, Niwa S, Shigeta S (2001). Immunological and PCR analyses for Borna disease virus in psychiatric patients and blood donors in Japan. *J Clin Microbiol* **39:** 419–429.

Furrer E, Bilzer T, Stitz L, Planz O (2001). Neutralizing antibodies in persistent borna disease virus infection: prophylactic effect of gp94-specific monoclonal antibodies in preventing encephalitis. *J Virol* **75:** 943–951.

Galabru J, Saron MF, Berg M, Berg AL, Herzog S, Labie J, Zientara S (2000). Borna disease virus antibodies in French horses. *Vet Rec* **147:** 721–722.

Gies U, Bilzer T, Stitz L, Staiger JF (1998). Disturbance of the cortical cholinergic innervation in Borna disease prior to encephalitis. *Brain Pathol* **8:** 39–48.

Gonzalez-Dunia D, Cubitt B, de la Torre JC (1998). Mechanism of Borna disease virus entry into cells. *J Virol* **72:** 783–788.

Gonzalez-Dunia D, Cubitt B, Grasser FA, de la Torre JC (1997). Characterization of Borna disease virus p56 protein, a surface glycoprotein involved in virus entry. *J Virol* **71:** 3208–3218.

Gosztonyi G, Ludwig H (2001). Interactions of viral proteins with neurotransmitter receptors may protect or destroy neurons. *Curr Top Microbiol Immunol* **253:** 121–144.

Haase CG, Viazov S, Fiedler M, Koenig N, Faustmann PM, Roggendorf M (2001). Borna disease virus RNA is absent in chronic multiple sclerosis. *Ann Neurol* **50:** 423–424.

Haga S, Yoshimura M, Motoi Y, Arima K, Aizawa T, Ikuta K, Tashiro M, Ikeda K (1997). Detection of Borna disease virus genome in normal human brain tissue. *Brain Res* **770:** 307–309.

Hagiwara K, Asakawa M, Liao L, Jiang W, Yan S, Chai J, Oku Y, Ikuta K, Ito M (2001). Seroprevalence of Borna disease virus in domestic animals in Xinjiang, China. *Vet Microbiol* **80:** 383–389.

Hagiwara K, Kamitani W, Takamura S, Taniyama H, Nakaya T, Tanaka H, Kirisawa R, Iwai H, Ikuta K (2000). Detection of Borna disease virus in a pregnant mare and her fetus. *Vet Microbiol* **72:** 207–216.

Hagiwara K, Kawamoto S, Takahashi H, Nakamura Y, Nakaya T, Hiramune T, Ishihara C, Ikuta K (1997a). High prevalence of Borna disease virus infection in healthy sheep in Japan. *Clin Diagn Lab Immunol* **4:** 339–344.

Hagiwara K, Momiyama N, Taniyama H, Nakaya T, Tsunoda N, Ishihara C, Ikuta K (1997b). Demonstration of Borna disease virus (BDV) in specific regions of the brain from horses positive for serum antibodies to BDV but negative for BDV RNA in the blood and internal organs. *Med Microbiol Immunol (Berl)* **186:** 19–24.

Hagiwara K, Nakaya T, Nakamura Y, Asahi S, Takahashi H, Ishihara C, Ikuta K (1996). Borna disease virus RNA in peripheral blood mononuclear cells obtained from healthy dairy cattle. *Med Microbiol Immunol (Berl)* **185:** 145–151.

Hallensleben W, Zocher M, Staeheli P (1997). Borna disease virus is not sensitive to amantadine. *Arch Virol* **142:** 2043–2048.

Hamner MB, Diamond BI (1996). Plasma dopamine and norepinephrine correlations with psychomotor retardation, anxiety, and depression in non-psychotic depressed patients: a pilot study. *Psychiatry Res* **64:** 209–211.

Hans A, Syan S, Crosio C, Sassone-Corsi P, Brahic M, Gonzalez-Dunia D (2001). Borna disease virus persistent infection activates mitogen-activated protein kinase and blocks neuronal differentiation of PC12 cells. *J Biol Chem* **276:** 7258–7265.

Hatalski CG (1996). Alterations in the immune response within the central nervous system of rats infected with Borna disease virus: potential mechanisms for viral persistence. PhD Thesis, University of California Irvine, Irvine, CA.

Hatalski CG, Hickey WF, Lipkin WI (1998). Evolution of the immune response in the central nervous system following infection with Borna disease virus. *J Neuroimmunol* **90:** 137–142.

Hatalski CG, Kliche S, Stitz L, Lipkin WI (1995). Neutralizing antibodies in Borna disease virus-infected rats. *J Virol* **69:** 741–747.

Hatalski CG, Lewis AJ, Lipkin WI (1997). Borna disease. *Emerg Infect Dis* **3:** 129–135.

Helps CR, Turan N, Bilal T, Harbour DA, Yilmaz H (2001). Detection of antibodies to Borna disease virus in Turkish cats by using recombinant p40. *Vet Rec* **149:** 647–650.

Hirano N, Kao M, Ludwig H (1983). Persistent, tolerant or subacute infection in Borna disease virus-infected rats. *J Gen Virol* **64:** 1521–1530.

Horii Y, Garcia NP, Noviana D, Kono F, Sawada T, Naraki T, Yamaguchi K (2001). Detection of anti-borna disease virus antibodies from cats in Asian countries, Japan, Philippines and Indonesia using electrochemiluminescence immunoassay. *J Vet Med Sci* **63:** 921–923.

Hornig M, Briese T, Lipkin WI (2001). Bornavirus tropism and targeted pathogenesis: virus-host interactions in a neurodevelopmental model. *Adv Virus Res* **56:** 557–582.

Hornig M, Weissenböck H, Horscroft N, Lipkin WI (1999). An infection-based model of neurodevelopmental damage. *Proc Natl Acad Sci USA* **96:** 12102–12107.

Igata-Yi R, Yamaguchi K, Yoshiki K, Takemoto S, Yamasaki H, Matsuoka M, Miyakawa T (1996). Borna disease virus and the consumption of raw horse meat [letter]. *Nat Med* **2:** 948–949.

Iwahashi K, Watanabe M, Nakamura K, Suwaki H, Nakaya T, Nakamura Y, Takahashi H, Ikuta K (1997). Clinical investigation of the relationship between Borna disease virus (BDV) infection and schizophrenia in 67 patients in Japan. *Acta Psychiatr Scand* **96:** 412–415.

Iwata Y, Takahashi K, Peng X, Fukuda K, Ohno K, Ogawa T, Gonda K, Mori N, Niwa S, Shigeta S (1998). Detection

and sequence analysis of borna disease virus p24 RNA from peripheral blood mononuclear cells of patients with mood disorders or schizophrenia and of blood donors. *J Virol* **72:** 10044–10049.

Kamitani W, Shoya Y, Kobayashi T, Watanabe M, Lee BJ, Zhang G, Tomonaga K, Ikuta K (2001). Borna disease virus phosphoprotein binds a neurite outgrowth factor, amphoterin/HMG-1. *J Virol* **75:** 8742–8751.

Kane J, Marder J (1993). Psychopharmacologic treatments of schizophrenia. *Schizophr Bull* **19:** 287–302.

Kao M, Hamir AN, Rupprecht CE, Fu ZF, Shankar V, Koprowski H, Dietzschold B (1993). Detection of antibodies against Borna disease virus in sera and cerebrospinal fluid of horses in the USA. *Vet Rec* **132:** 241–244.

Kao M, Ludwig H, Gosztonyi G (1984). Adaptation of Borna disease virus to the mouse. *J Gen Virol* **65:** 1845–1849.

Karpas WJ, Peterson JD, Miller SD (1994). Anergy in vivo: downregulation of antigen-specific CD4+ Th1 but not Th2 cytokine responses. *Int Immunol* **6:** 721–730.

Kelsoe JR, Savodnick AD, Kristbjarnarson H, Bergesch P, Mroczkowski-Parker Z, Drennan M, Rapaport MH, Flodman P, Spence MA, Remick RA (1996). Possible locus for bipolar disorder near the dopamine transporter on chromosome 5. *Am J Med Genet* **67:** 533–540.

Kemper TL, Bauman ML (1993). The contribution of neuropathologic studies to the understanding of autism. *Neurol Clin North Am* **11:** 175–187.

Khoury SJ, Akalin E, Chandraker A, Turka LA, Linsley PS, Sayegh MH, Hancock WW (1995). CD28-B7 costimulatory blockade by CTLA4Ig prevents actively induced experimental autoimmune encephalomyelitis and inhibits Th1 but spares Th2 cytokines in the central nervous system. *J Immunol* **155:** 4521–4524.

Kiermayer S, Kraus I, Richt JA, Garten W, Eickmann M (2002). Identification of the amino terminal subunit of the glycoprotein of Borna disease virus. *FEBS Lett* **531:** 255–258.

Kilbourne ED (1991). New viruses and new disease: mutation, evolution and ecology. *Curr Opin Immunol* **3:** 518–524.

Kim YK, Kim SH, Choi SH, Ko YH, Kim L, Lee MS, Suh KY, Kwak DI, Song KJ, Lee YJ, Yanagihara R, Song JW (1999). Failure to demonstrate Borna disease virus genome in peripheral blood mononuclear cells from psychiatric patients in Korea. *J NeuroVirol* **5:** 196–199.

Kishi M, Arimura Y, Ikuta K, Shoya Y, Lai PK, Kakinuma M (1996). Sequence variability of Borna disease virus open reading frame II found in human peripheral blood mononuclear cells. *J Virol* **70:** 635–640.

Kishi M, Nakaya T, Nakamura Y, Kakinuma M, Takahashi TA, Sekiguchi S, Uchikawa M, Tadokoro K, Ikeda K, Ikuta K (1995a). Prevalence of Borna disease virus RNA in peripheral blood mononuclear cells from blood donors. *Med Microbiol Immunol (Berl)* **184:** 135–138.

Kishi M, Nakaya T, Nakamura Y, Zhong Q, Ikeda K, Senjo M, Kakinuma M, Kato S, Ikuta K (1995b). Demonstration of human Borna disease virus RNA in human peripheral blood mononuclear cells. *FEBS Lett* **364:** 293–297.

Kitani T, Kuratsune H, Fuke I, Nakamura Y, Nakaya T, Asahi S, Tobiume M, Yamaguti K, Machii T, Inagi R, Yamanishi K, Ikuta K (1996). Possible correlation between Borna disease virus infection and Japanese patients with chronic fatigue syndrome. *Microbiol Immunol* **40:** 459–462.

Kitze B, Herzog S, Rieckmann P, Poser S, Richt J (1996). No evidence of Borna disease virus-specific antibodies in multiple sclerosis patients in Germany [letter]. *J Neurol* **243:** 660–662.

Kobayashi T, Kamitani W, Zhang G, Watanabe M, Tomonaga K, Ikuta K (2001). Borna disease virus nucleoprotein requires both nuclear localization and export activities for viral nucleocytoplasmic shuttling. *J Virol* **75:** 3404–34012.

Kobayashi T, Shoya Y, Koda T, Takashima I, Lai PK, Ikuta K, Kakinuma M, Kishi M (1998). Nuclear targeting activity associated with the amino terminal region of the Borna disease virus nucleoprotein. *Virology* **243:** 188–197.

Konradi C, Kobierski LA, Nguyen TV, Heckers S, Hyman SE (1993). The cAMP-response-element-binding protein interacts, but Fos protein does not interact, with the proenkephalin enhancer in rat striatum. *Proc Natl Acad Sci USA* **90:** 7005–7009.

Kubo K, Fujiyoshi T, Yokoyama MM, Kamei K, Richt JA, Kitze B, Herzog S, Takigawa M, Sonoda S (1997). Lack of association of Borna disease virus and human T-cell leukemia virus type 1 infections with psychiatric disorders among Japanese patients. *Clin Diagn Lab Immunol* **4:** 189–194.

Lebain P, Vabret A, Freymuth F, Brazo P, Chabot B, Dollfus S, Henri B (2002). Borna disease virus and psychiatric disorders. *Schizophr Res* **57:** 303–305.

Lieb K, Hallensleben W, Czygan M, Stitz L, Staeheli P (1997). No Borna disease virus-specific RNA detected in blood from psychiatric patients in different regions of Germany. The Bornavirus Study Group [letter]. *Lancet* **350:** 1002.

Lipkin WI, Carbone KM, Wilson MC, Duchala CS, Narayan O, Oldstone MB (1988). Neurotransmitter abnormalities in Borna disease. *Brain Res* **475:** 366–370.

Lipkin WI, Hornig M, Briese T (2001). Borna disease virus and neuropsychiatric disease—a reappraisal. *Trends Microbiol* **9:** 295–298.

Lipkin WI, Travis GH, Carbone KM, Wilson MC (1990). Isolation and characterization of Borna disease agent cDNA clones. *Proc Natl Acad Sci U S A* **87:** 4184–4188.

Ludwig H, Bode L, Gosztonyi G (1988). Borna disease: a persistent virus infection of the central nervous system. *Prog Med Virol* **35:** 107–151.

Lundgren AL, Czech G, Bode L, Ludwig H (1993). Natural Borna disease in domestic animals others than horses and sheep. *Zentralbl Veterinarmed [B]* **40:** 298–303.

Malkinson M, Weisman Y, Ashash E, Bode L, Ludwig H (1993). Borna disease in ostriches [letter; comment]. *Vet Rec* **133:** 304.

Nakamura Y, Asahi S, Nakaya T, Bahmani MK, Saitoh S, Yasui K, Mayama H, Hagiwara K, Ishihara C, Ikuta K (1996). Demonstration of borna disease virus RNA in peripheral blood mononuclear cells derived from domestic cats in Japan. *J Clin Microbiol* **34:** 188–191.

Nakamura Y, Kishi M, Nakaya T, Asahi S, Tanaka H, Sentsui H, Ikeda K, Ikuta K (1995). Demonstration of Borna disease virus RNA in peripheral blood mononuclear cells from healthy horses in Japan. *Vaccine* **13:** 1076–1079.

Nakamura Y, Takahashi H, Shoya Y, Nakaya T, Watanabe M, Tomonaga K, Iwahashi K, Ameno K, Momiyama N, Taniyama H, Sata T, Kurata T, de la Torre JC, Ikuta K (2000). Isolation of Borna disease virus from human brain tissue. *J Virol* **74:** 4601–4611.

Nakamura Y, Watanabe M, Kamitani W, Taniyama H, Nakaya T, Nishimura Y, Tsujimoto H, Machida S, Ikuta K (1999). High prevalence of Borna disease virus in domestic cats with neurological disorders in Japan. *Vet Microbiol* **70:** 153–169.

Nakaya T, Kuratsune H, Kitani T, Ikuta K (1997). [Demonstration on Borna disease virus in patients with chronic fatigue syndrome]. *Nippon Rinsho* **55:** 3064–3071.

Nakaya T, Takahashi H, Nakamura Y, Asahi S, Tobiume M, Kuratsune H, Kitani T, Yamanishi K, Ikuta K (1996). Demonstration of Borna disease virus RNA in peripheral blood mononuclear cells derived from Japanese patients with chronic fatigue syndrome. *FEBS Lett* **378:** 145–149.

Nakaya T, Takahashi H, Nakamura Y, Kuratsune H, Kitani T, Machii T, Yamanishi K, Ikuta K (1999). Borna disease virus infection in two family clusters of patients with chronic fatigue syndrome. *Microbiol Immunol* **43:** 679–689.

Narayan O, Herzog S, Frese K, Scheefers H, Rott R (1983). Pathogenesis of Borna disease in rats: immune-mediated viral ophthalmoencephalopathy causing blindness and behavioral abnormalities. *J Infect Dis* **148:** 305–315.

Nishino Y, Kobasa D, Rubin SA, Pletnikov MV, Carbone KM (2002). Enhanced neurovirulence of borna disease virus variants associated with nucleotide changes in the glycoprotein and L polymerase genes. *J Virol* **76:** 8650–8658.

Nowotny N, Kolodziejek J, Jehle CO, Suchy A, Staeheli P, Schwemmle M (2000). Isolation and characterization of a new subtype of Borna disease virus. *J Virol* **74:** 5655–5658.

Okamoto M, Kagawa Y, Kamitani W, Hagiwara K, Kirisawa R, Iwai H, Ikuta K, Taniyama H (2002). Borna disease in a dog in Japan. *J Comp Pathol* **126:** 312–317.

Partonen T (1996). Dopamine and circadian rhythms in seasonal affective disorder. *Med Hyp* **47:** 191–192.

Perez M, Watanabe M, Whitt MA, de la Torre JC (2001). N-terminal domain of Borna disease virus G (p56) protein is sufficient for virus receptor recognition and cell entry. *J Virol* **75:** 7078–7085.

Planz O, Pleschka S, Ludwig S (2001). MEK-specific inhibitor U0126 blocks spread of Borna disease virus in cultured cells. *J Virol* **75:** 4871–4877.

Planz O, Rentzsch C, Batra A, Rziha HJ, Stitz L (1998). Persistence of Borna disease virus-specific nucleic acid in blood of psychiatric patient [letter]. *Lancet* **352:** 623.

Planz O, Rentzsch C, Batra A, Winkler T, Buttner M, Rziha HJ, Stitz L (1999). Pathogenesis of borna disease virus: granulocyte fractions of psychiatric patients harbor infectious virus in the absence of antiviral antibodies. *J Virol* **73:** 6251–6256.

Pleschka S, Staeheli P, Kolodziejek J, Richt JA, Nowotny N, Schwemmle M (2001). Conservation of coding potential and terminal sequences in four different isolates of Borna disease virus. *J Gen Virol* **82:** 2681–2690.

Pletnikov MV, Rubin SA, Carbone KM, Moran TH, Schwartz GJ (2001). Neonatal Borna disease virus infection (BDV)–induced damage to the cerebellum is associated with sensorimotor deficits in developing Lewis rats. *Brain Res Dev Brain Res* **126:** 1–12.

Pletnikov MV, Rubin SA, Schwartz GJ, Moran TH, Sobotka TJ, Carbone KM (1999a). Persistent neonatal Borna disease virus (BDV) infection of the brain causes chronic emotional abnormalities in adult rats. *Physiol Behav* **66:** 823–831.

Pletnikov MV, Rubin SA, Vasudevan K, Moran TH, Carbone KM (1999b). Developmental brain injury associated with abnormal play behavior in neonatally Borna disease virus-infected Lewis rats: a model of autism. *Behav Brain Res* **100:** 43–50.

Pyper JM, Gartner AE (1997). Molecular basis for the differential subcellular localization of the 38- and 39-kilodalton structural proteins of Borna disease virus. *J Virol* **71:** 5133–5139.

Rauer M, Pagenstecher A, Schulte-Monting J, Sauder C (2002). Upregulation of chemokine receptor gene expression in brains of Borna disease virus (BDV)-infected rats in the absence and presence of inflammation. *J NeuroVirol* **8:** 168–179.

Reeves NA, Helps CR, Gunn-Moore DA, Blundell C, Finnemore PL, Pearson GR, Harbour DA (1998). Natural Borna disease virus infection in cats in the United Kingdom [In Process Citation]. *Vet Rec* **143:** 523–526.

Richt JA, Alexander RC, Herzog S, Hooper DC, Kean R, Spitsin S, Bechter K, Schuttler R, Feldmann H, Heiske A, Fu ZF, Dietzschold B, Rott R, Koprowski H (1997). Failure to detect Borna disease virus infection in peripheral blood leukocytes from humans with psychiatric disorders. *J NeuroVirol* **3:** 174–178.

Richt JA, Furbringer T, Koch A, Pfeuffer I, Herden C, Bause-Niedrig I, Garten W (1998). Processing of the Borna disease virus glycoprotein gp94 by the subtilisin-like endoprotease furin. *J Virol* **72:** 4528–4533.

Rott R, Herzog S, Bechter K, Frese K (1991). Borna disease, a possible hazard for man. *Arch Virol* **118:** 143–149.

Rott R, Herzog S, Fleischer B, Winokur A, Amsterdam J, Dyson W, Koprowski H (1985). Detection of serum antibodies to Borna disease virus in patients with psychiatric disorders. *Science* **228:** 755–756.

Rubin SA, Sierra-Honigmann AM, Lederman HM, Waltrip RW 2nd, Eiden JJ, Carbone KM (1995). Hematologic consequences of Borna disease virus infection of rat bone marrow and thymus stromal cells. *Blood* **85:** 2762–2769.

Rubin SA, Sylves P, Vogel M, Pletnikov M, Moran TH, Schwartz GJ, Carbone KM (1999). Borna disease virus-induced hippocampal dentate gyrus damage is associated with spatial learning and memory deficits. *Brain Res Bull* **48:** 23–30.

Rybakowski F, Sawada T, Yamaguchi K (2001a). Borna disease virus-reactive antibodies and recent-onset psychiatric disorders. *Eur Psychiatry* **16:** 191–192.

Rybakowski F, Sawada T, Yamaguchi K, Rajewski A, Rybakowski J (2002). Borna disease virus–reactive antibodies in Polish psychiatric patients. *Med Sci Monit* **8:** CR642–CR646.

Rybakowski F, Yamaguchi K, Krzyminski S, Zmyslony F, Biernat J, Kocialkowski M, Tandeck A, Trafarska B, Zalejski M, Sawada T, Naraki T, Czerski P, Rajewski A, Rybakowski JK (2001b). [Detection of anti-Borna disease virus antibodies in patients hospitalized in psychiatric hospitals located in the mid-Western region of Poland]. *Psychiatr Pol* **35:** 819–829.

Salvatore M, Morzunov S, Schwemmle M, Lipkin WI (1997). Borna disease virus in brains of North American and European people with schizophrenia and bipolar disorder. Bornavirus Study Group [letter]. *Lancet* **349:** 1813–1814.

Sauder C, de la Torre JC (1999). Cytokine expression in the rat central nervous system following perinatal Borna disease virus infection. *J Neuroimmunol* **96:** 29–45.

Sauder C, Hallensleben W, Pagenstecher A, Schneckenburger S, Biro L, Pertlik D, Hausmann J, Suter M, Staeheli P (2000). Chemokine gene expression in astrocytes of Borna disease virus-infected rats and mice in the absence of inflammation. *J Virol* **74:** 9267–9280.

Sauder C, Muller A, Cubitt B, Mayer J, Steinmetz J, Trabert W, Ziegler B, Wanke K, Mueller-Lantzsch N, de la Torre JC, Grasser FA (1996). Detection of Borna disease virus (BDV) antibodies and BDV RNA in psychiatric patients: evidence for high sequence conservation of human blood-derived BDV RNA. *J Virol* **70:** 7713–7724.

Schneemann A, Schneider PA, Kim S, Lipkin WI (1994). Identification of signal sequences that control transcription of borna disease virus, a nonsegmented, negative-strand RNA virus. *J Virol* **68:** 6514–6522.

Schneemann A, Schneider PA, Lamb RA, Lipkin WI (1995). The remarkable coding strategy of borna disease virus: a new member of the nonsegmented negative strand RNA viruses. *Virology* **210:** 1–8.

Schneider PA, Briese T, Zimmermann W, Ludwig H, Lipkin WI (1994a). Sequence conservation in field and experimental isolates of Borna disease virus. *J Virol* **68:** 63–68.

Schneider PA, Hatalski CG, Lewis AJ, Lipkin WI (1997a). Biochemical and functional analysis of the Borna disease virus G protein. *J Virol* **71:** 331–336.

Schneider PA, Kim R, Lipkin WI (1997b). Evidence for translation of the Borna disease virus G protein by leaky ribosomal scanning and ribosomal reinitiation. *J Virol* **71:** 5614–5619.

Schneider PA, Schneemann A, Lipkin WI (1994b). RNA splicing in Borna disease virus, a nonsegmented, negative-strand RNA virus. *J Virol* **68:** 5007–5012.

Schwartz RH (1992). Costimulation of T lymphocytes: the role of CD28, CTLA-4 and B4/BB1 in interleukin-2 production and immunotherapy. *Cell* **71:** 1065–1068.

Schwemmle M (2001). Borna disease virus infection in psychiatric patients: are we on the right track? *Lancet Infect Dis* **1:** 46–52.

Schwemmle M, De B, Shi L, Banerjee A, Lipkin WI (1997). Borna disease virus P-protein is phosphorylated by protein kinase Cepsilon and casein kinase II. *J Biol Chem* **272:** 21818–21823.

Schwemmle M, Jehle C, Formella S, Staeheli P (1999a). Sequence similarities between human bornavirus isolates and laboratory strains question human origin. *Lancet* **354:** 1973–1974.

Schwemmle M, Jehle C, Shoemaker T, Lipkin WI (1999b). Characterization of the major nuclear localization signal of the Borna disease virus phosphoprotein. *J Gen Virol* **80:** 97–100.

Schwemmle M, Salvatore M, Shi L, Richt J, Lee CH, Lipkin WI (1998). Interactions of the borna disease virus P, N, and X proteins and their functional implications. *J Biol Chem* **273:** 9007–9012.

Selten JP, van Vliet K, Pleyte W, Herzog S, Hoek HW, van Loon AM (2000). Borna disease virus and schizophrenia in Surinamese immigrants to the Netherlands. *Med Microbiol Immunol (Berl)* **189:** 55–57.

Shoya Y, Kobayashi T, Koda T, Ikuta K, Kakinuma M, Kishi M (1998). Two proline-rich nuclear localization signals in the amino- and carboxyl-terminal regions of the Borna disease virus phosphoprotein. *J Virol* **72:** 9755–9762.

Sierra-Honigmann AM, Carbone KM, Yolken RH (1995). Polymerase chain reaction (PCR) search for viral nucleic acid sequences in schizophrenia. *Br J Psychiatry* **166:** 55–60.

Sierra-Honigmann AM, Rubin SA, Estafanous MG, Yolken RH, Carbone KM (1993). Borna disease virus in peripheral blood mononuclear and bone marrow cells of neonatally and chronically infected rats. *J Neuroimmunol* **45:** 31–36.

Soares JC, Mann JJ (1997). The anatomy of mood disorders—review of structural neuroimaging studies. *Biol Psychiatry* **41:** 86–106.

Sobbe M, Bilzer T, Gommel S, Noske K, Planz O, Stitz L (1997). Induction of degenerative brain lesions after adoptive transfer of brain lymphocytes from Borna disease virus-infected rats: presence of CD8+ T cells and perforin mRNA. *J Virol* **71:** 2400–2407.

Solbrig MV, Fallon JH, Lipkin WI (1995). Behavioral disturbances and pharmacology of Borna disease. *Curr Top Microbiol Immunol* **190:** 93–101.

Solbrig MV, Koob GF, Fallon JH, Lipkin WI (1994). Tardive dyskinetic syndrome in rats infected with Borna disease virus. *Neurobiol Dis* **1:** 111–119.

Solbrig MV, Koob GF, Fallon JH, Reid S, Lipkin WI (1996a). Prefrontal cortex dysfunction in Borna disease virus (BDV)–infected rats. *Biol Psychiatry* **40:** 629–636.

Solbrig MV, Koob GF, Joyce JN, Lipkin WI (1996b). A neural substrate of hyperactivity in Borna disease: changes in brain dopamine receptors. *Virology* **222:** 332–338.

Solbrig MV, Koob GF, Lipkin WI (1998). Cocaine sensitivity in Borna disease virus-infected rats. *Pharmacol Biochem Behav* **59:** 1047–1052.

Solbrig MV, Koob GF, Lipkin WI (2002). Key role for enkephalinergic tone in cortico-striatal-thalamic function. *Eur J Neurosci* **16:** 1819–1822.

Solbrig MV, Koob GF, Parsons LH, Kadota T, Horscroft N, Briese T, Lipkin WI (2000). Neurotrophic factor expression after CNS viral injury produces enhanced sensitivity to psychostimulants: potential mechanism for addiction vulnerability. *J Neurosci* **20:** RC104.

Staeheli P, Lieb K (2001). Bornavirus and psychiatric disorders—fact or fiction? *J Med Microbiol* **50:** 579–581.

Stitz L, Noske K, Planz O, Furrer E, Lipkin WI, Bilzer T (1998a). A functional role for neutralizing antibodies in Borna disease: influence on virus tropism outside the central nervous system. *J Virol* **72:** 8884–8892.

Stitz L, Planz O, Bilzer T (1998b). Lack of antiviral effect of amantadine in Borna disease virus infection. *Med Microbiol Immunol (Berl)* **186:** 195–200.

Takahashi H, Nakaya T, Nakamura Y, Asahi S, Onishi Y, Ikebuchi K, Takahashi TA, Katoh T, Sekiguchi S, Takazawa M, Tanaka H, Ikuta K (1997). Higher prevalence of Borna disease virus infection in blood donors living near thoroughbred horse farms. *J Med Virol* **52:** 330–335.

Tomonaga K, Kobayashi T, Lee BJ, Watanabe M, Kamitani W, Ikuta K (2000). Identification of alternative splicing and negative splicing activity of a nonsegmented negative-strand RNA virus, Borna disease virus. *Proc Natl Acad Sci USA* **97:** 12788–12793.

Tsuji K, Toyomasu K, Imamura Y, Maeda H, Toyoda T (2000). No association of borna disease virus with psychiatric disorders among patients in northern Kyushu, Japan. *J Med Virol* **61:** 336–340.

Tsujimura K, Mizutani T, Kariwa H, Yoshimatsu K, Ogino M, Morii Y, Inagaki H, Arikawa J, Takashima I (1999). A serosurvey of Borna disease virus infection in wild rats

by a capture ELISA [In Process Citation]. *J Vet Med Sci* **61:** 113–117.

Vahlenkamp TW, Enbergs HK, Muller H (2000). Experimental and natural borna disease virus infections: presence of viral RNA in cells of the peripheral blood. *Vet Microbiol* **76:** 229–244.

VandeWoude S, Richt J, Zink M, Rott R, Narayan O, Clements J (1990). A Borna virus cDNA encoding a protein recognized by antibodies in humans with behavioral diseases. *Science* **250:** 1276–1281.

Walker MP, Jordan I, Briese T, Fischer N, Lipkin WI (2000). Expression and characterization of the Borna disease virus polymerase. *J Virol* **74:** 4425–4428.

Walker MP, Lipkin WI (2002). Characterization of the nuclear localization signal of the borna disease virus polymerase. *J Virol* **76:** 8460–8467.

Waltrip RW 2nd, Buchanan RW, Carpenter WT Jr, Kirkpatrick B, Summerfelt A, Breier A, Rubin SA, Carbone KM (1997). Borna disease virus antibodies and the deficit syndrome of schizophrenia. *Schizophr Res* **23:** 253–257.

Waltrip RW 2nd, Buchanan RW, Summerfelt A, Breier A, Carpenter WT Jr, Bryant NL, Rubin SA, Carbone KM (1995). Borna disease virus and schizophrenia. *Psychiatry Res* **56:** 33–44.

Weisman Y, Huminer D, Malkinson M, Meir R, Kliche S, Lipkin WI, Pitlik S (1994). Borna disease virus antibodies among workers exposed to infected ostriches [letter]. *Lancet* **344:** 1232–1233.

Weissenböck H, Hornig M, Hickey WF, Lipkin WI (2000). Microglial activation and neuronal apoptosis in Bornavirus infected neonatal Lewis rats. *Brain Pathol* **10:** 260–272.

Weissenbock H, Nowotny N, Caplazi P, Kolodziejek J, Ehrensperger F (1998). Borna disease in a dog with lethal meningoencephalitis. *J Clin Microbiol* **36:** 2127–2130.

Wittrup IH, Christensen LS, Jensen B, Danneskiold-Samsee B, Bliddal H, Wiik A (2000). Search for Borna disease virus in Danish fibromyalgia patients. *Scand J Rheumatol* **29:** 387–390.

Wolff T, Unterstab G, Heins G, Richt JA, Kann M (2002). Characterization of an unusual importin alpha binding motif in the borna disease virus p10 protein that directs nuclear import. *J Biol Chem* **277:** 12151–12157.

Yamaguchi K, Sawada T, Naraki T, Igata-Yi R, Shiraki H, Horii Y, Ishii T, Ikeda K, Asou N, Okabe H, Mochizuki M, Takahashi K, Yamada S, Kubo K, Yashiki S, Waltrip RW, 2nd, Carbone KM (1999). Detection of borna disease virus-reactive antibodies from patients with psychiatric disorders and from horses by electrochemiluminescence immunoassay. *Clin Diagn Lab Immunol* **6:** 696–700.

Yilmaz H, Helps CR, Turan N, Uysal A, Harbour DA (2002). Detection of antibodies to Borna disease virus (BDV) in Turkish horse sera using recombinant p40. Brief report. *Arch Virol* **147:** 429–435.

Zimmermann W, Durrwald R, Ludwig H (1994). Detection of Borna disease virus RNA in naturally infected animals by a nested polymerase chain reaction. *J Virol Methods* **46:** 133–143.

Zocher M, Czub S, Schulte-Monting J, de La Torre JC, Sauder C (2000). Alterations in neurotrophin and neurotrophin receptor gene expression patterns in the rat central nervous system following perinatal Borna disease virus infection. *J NeuroVirol* **6:** 462–477.