Autoantibodies to Non-myelin Antigens as Contributors to the Pathogenesis of Multiple Sclerosis

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Abstract

For years, investigators have sought to prove that myelin antigens are the primary targets of autoimmunity in multiple sclerosis (MS). Recent experiments have begun to challenge this assumption, particularly when studying the neurodegenerative phase of MS. T-lymphocyte responses to myelin antigens have been extensively studied, and are likely early contributors to the pathogenesis of MS. Antibodies to myelin antigens have a much more inconstant association with the pathogenesis of MS. Recent studies indicate that antibodies to non-myelin antigens such as neurofilaments, neurofascin, RNA binding proteins and potassium channels may contribute to the pathogenesis of MS. The purpose of this review is to analyze recent studies that examine the role that autoantibodies to non-myelin antigens might play in the pathogenesis of MS.

Keywords: Multiple sclerosis; Neurodegeneration; Heterogeneous nuclear ribonucleoprotein A1 (hnRNP A1); Autoimmunity; Spastic paraparesis; RNA binding protein; Human T-lymphotropic virus type 1 (HTLV-1)

Background

MS is the most common immune-mediated demyelinating disease of the central nervous system (CNS) in humans [1,2]. There are approximately 2 million MS cases worldwide and like most autoimmune diseases, MS disproportionately affects middle-aged women [1,2]. Initially, two-thirds of patients develop relapsing remitting MS (RRMS), in which neurologic symptoms occur followed by partial or complete recovery [1-4]. Following RRMS, a majority of patients (up to 90% within 25 years) develop secondary progressive MS (SPMS), manifested by neurological deterioration without relapses [1-5]. Approximately 15% of MS patients are diagnosed with primary progressive MS (PPMS), in which neurological symptoms progress from onset without relapses [1-4]. Therefore, the majority of patients develop progressive forms of MS during their lifetime. Symptoms of progressive forms of MS commonly involve the long tracts of the CNS, and include spastic paraparesis, sensory dysfunction, ataxia and urinary dysfunction [6,7].

Pathologically, the most obvious abnormalities of the CNS are 'MS plaques', areas of demyelination of white matter in a milieu of inflammatory cells (T-lymphocytes, B-lymphocytes, macrophages and plasma cells) [8]. A series of elegant studies also describe plaques involving gray matter; axonal and neuronal injury (known as neurodegeneration); as well as changes in inflammatory profiles related to the type of MS [4,5,9-20]. Since demyelination was considered the hallmark of MS, a plethora of studies examined the potential role that immune response to myelin proteins play in the pathogenesis of MS. The robust T-lymphocyte response in the plaque, the discovery of the T-cell receptor and it specificity related to HLA of its target cell; and the use of experimental allergic encephalomyelitis (EAE), a predominantly T-cell mediated model of MS, led to the study of T-cell responses to myelin targets as important hypotheses describing the pathogenesis of MS [21-37]. Many studies showed that T-lymphocytes from MS patients preferentially target myelin peptides derived from myelin basic protein (MBP), myelin oligodendrocyte glycoprotein (MOG), proteolipid protein (PLP) and myelin oligodendrocytic basic glycoprotein (MOBP) [28,38-44]. In addition, EAE is induced by many of these same myelin peptides or by adoptive transfer of T-cells isolated from animals immunized by myelin peptides [45,46]. Further, studies showed that Th1 and Th17 CD4+ T-cell responses were definite contributors to the pathogenesis of EAE and likely important in the pathogenesis of MS [36,37,47]. However, some of these observations were tempered by the realization that healthy controls also develop T-cell responses to myelin peptides. More recently, CD8+ T-cells have also been shown to contribute to the pathogenesis of EAE and MS [48-51].

In addition to cellular immune response, humoral responses to myelin protein antigens were extensively studied. Many of these studies led to conflicting results. Alternatively, experiments examined the role of both T-cell and antibody responses to non-myelin targets as contributors to pathogenesis of MS. Examples of important T-cell responses to non-myelin antigens include osteopontin, aB crystalline and contactin-2 [52-55]. Interestingly, antibody responses to non-myelin antigens such as neurofilaments, neurofascin, RNA binding proteins and potassium channels have also been recently implicated in the pathogenesis of MS, which will be the primary focus of this review [2,56-62].

Antibodies to Myelin Antigens

For more than 35 years, scientists have been studying whether antibodies to myelin protein antigens contribute to the diagnosis and pathogenesis of MS (Table 1). Antibodies from both serum and cerebrospinal fluid (CSF) were examined. Lisak et al. used immunofluorescence of serum IgG applied to monkey or guinea pig spinal cord sections on slides [63]. This group examined 41 MS...
patients. Controls included patients with amyotrophic lateral sclerosis (ALS), subacute sclerosing panencephalitis (SSPE), Guillain-Barre Syndrome (GBS) and healthy controls (HC). All groups were found to be immunoreact with myelin contained within spinal cord sections [63]. Patients with ALS, MS and GBS had greater titers than HCs, with ALS showing the highest titers [63]. Next, using radioimmunoassays (RIAs), a series of studies examined whether IgG isolated from the CSF of MS patients was specific for myelin basic protein (MBP) [64-66]. Although some studies showed differences between MS patients and patient without neurologic disease, the majority could not differentiate MS patients from patients with other neurologic diseases such as SSPE, GBS, ALS, or neurophilis [64-66]. With the advent of enzyme-linked immunosorbent assay (ELISA) and MOG as a target antigen, researchers began to use ELISA to study immunoreactivity to both MBP and MOG. One study showed that CSF from only 7/30 patients immunoreacted with MOG compared to 3/30 patients with other neurologic disease (OND) [67]. Using serial dilutions of serum and CSF, Reindl et al., showed little difference in immunoreactivity to MOG or MBP when comparing MS patients (n=132) with patients with other inflammatory neurological diseases (OIND) (n=32), (OND) (n=30) or rheumatoid arthritis patients (n=10) [68]. The highest percentage of positive antibodies titers to MOG and MBP were in patients with OIND [68]. Although there were some differences between the study groups, none were consistently in favor of MS [68]. Karni et al., used antibodies isolated from paired plasma and CSF samples of patients with MS, OIND and HC [69]. Interestingly, the OIND group included both inflammatory and neurodegenerative neurological diseases. In CSF, antibodies to MOG and MBP were elevated in both MS and OND compared to HC. In serum, titers were slightly elevated in MS patients compared to OIND, but the frequency of positive response was similar between the two groups [69]. This led the authors to conclude that anti-MOG antibodies were not specific for MS [69].

In 2003, Berger et al., reported the results of a study examining whether serum IgM antibodies to MOG and MBP in patients with clinically isolated syndrome (CIS) might predict conversion to clinically definite MS (CDMS) [70]. Using Western blots, this study showed that CIS patients with antibodies to both MBP and MOG were more likely to develop an MS relapse, have a shorter time period to relapse and a dramatically increased risk for developing CDMS (approaching 100%) compared to CIS patients who were negative for both antigens [70]. Patients who were positive for MOG but negative for MBP had an intermediate risk for developing a relapse and CDMS [70]. These data were replicated in a smaller study (n=31) [71]. Interestingly, a separate study showed the risk of conversion from CIS to CDMS correlated with the Poser diagnostic criteria for MS, but not the more recently developed McDonald criteria [72]. None of these studies analyzed IgM responses to HCs. When HCs were analyzed, associations between anti-myelin antibodies and MS were more difficult to prove. For example, several studies reported no differences in serum anti-MOG IgG or IgM levels in MS patients compared to patients with OIND or HC [73-75]. In one study, there was a two-fold increase in risk of MS in anti-MOG positive patients, however, the association dissolved after adjustment to antibodies to Epstein-Barr virus [76]. In a separate study, when HCs were included in the study of MS (not CIS), there was no significance between groups when analyzing anti-MOG IgM [77]. Data were significant when studying IgG and IgA antibodies to MOG, however the overlap in raw values in the MS and control groups were so close as to question their utility in defining the disease state [77]. In 2005, a small studied (47 CIS patients) showed no correlation between anti-MOG or anti-MBP antibodies and the development of CDMS (by either Poser or McDonald criteria) [78]. In 2007, Kühle and Pohl et al. used MOG and MBP Western blots to analyze serum IgG and IgM anti-MOG and anti-MBP antibodies in 462 CIS patients [79]. Their data showed no association between antibodies to either MOG or MBP and the risk for CIS patients developing CDMS [79]. Several studies continued to analyze the contribution of anti-MOG and anti-MBP antibodies to the diagnosis and pathogenesis of MS. Using a cell-based assay in which conformational epitopes can be detected, Lalive et al, showed differences in anti-MOG antibodies in RRMS, and SPMS compared to HC, but not PPMS [80]. However, using the same assay, Menge et al., showed that there was no difference in anti-MOG antibodies in MS patients compared to HCs [81]. In addition, in 72 MS patients who underwent brain biopsy of variable pathogenic MS subtypes (12 pattern 1, 43 pattern II, 17 pattern III) none showed a correlation between anti-MOG status (by either ELISA or Western blot) and conversion to CDMS [82]. Subsequently, multiple studies (using a number of different technologies) have shown little or no differences in anti-MOG and anti-MBP antibodies between neither MS and control patients nor associations with the development of CIS or CDMS [83-86]. Taken together, these data suggest that in humans, anti-myelin antibodies cannot be consistently utilized to diagnose MS, and are unlikely contributors to the pathogenesis of MS. These conclusions are further supported by Owens et al., who examined recombinant monoclonal antibodies derived from the light-chain variable region sequences of B- and plasma cells isolated from the CSF of MS patients for immunoreactivity to MBP, PLP and MOG [87]. Notably, none of the recombinant antibodies reacted with these three common myelin antigens [87]. These data suggest that myelin may not be the primary target for a pathogenic antibody response in MS and other CNS antigens, such as to neurons, axons and glia, may be important contributors to the pathogenesis of MS.

Antibodies to Non-myelin Self-antigens

In 1997, Rawes et al., examined the immunoreactivity of MS IgG to axonal plasma membranes, known as the axolemma enriched fraction (AEF) [88] (Table 1). The authors hypothesized that target antigens in the AEF escaped self-tolerance and immune surveillance because of myelin coating of the axons. Following demyelination, cryptic antigens would be available to the acquired immune response for antibodies to develop. They measured immunoreactivity of IgG in the serum and CSF from MS and control patients to the AEF. There was no immunoreactivity in HC. Immunoreactivity (measured by ELISA as mean absorbance) was greater in both the CSF and sera of MS compared to OIND. Interestingly, there was no correlation between these values and immunoreactivity to myelin antigens [88].

Gangliosides are predominantly axonal antigens, and are also minor components of the myelin sheath [89]. As early as 1980, studies indicated that MS patients developed antibodies to different gangliosides, however many of these studies were made up of small groups and incompletely controlled [89]. In 1998, Sadatipour et al., reported the results of immunoglobulin immunoreactivity to a series of gangliosides (GM1, GM3, GD1a, GD1b, and GD3) in MS patients (n=70; 33 RRMS, 21 SPMS, 16 PPMS), patients with OIND (n=41) and HCs (n=38) [89]. There were significant differences between progressive forms of MS and the other test groups (including RRMS) to a number of the gangliosides, with the anti-GM3 being the most robust response in PPMS and SPMS compared to RRMS, OIND and HCs [89].

Neurofilaments (NF) are major constituents of the axonal cytoskeleton and play critical roles in axonal radial growth,
maintenance of axon caliber and transmission of electrical impulses [56,90]. NF-L (68 kDa ‘light’ subunit) is a primary component of the NF core. NF-H (200 kDa, ‘heavy’) is located peripherally. Silber et al., showed that intrathecal production of anti-NF-L IgG antibodies were significantly elevated in PPMMS and SPMS patients compared to controls (OND, OIND, HC) [56]. In addition, oligoclonal bands were found to immunoreact with NF-L and anti-NF-L antibodies correlated with disability as calculated by the Expanded Disability Status Scale (EDSS) [56]. There were no correlations with antibodies detected in serum [56]. In a related study, Eikelenboom et al., examined potential correlations between anti-NF-L antibodies and cerebral atrophy [57]. The authors found a strong correlation between intrathecal anti-NF-L antibodies (the ‘anti-NF-L index’) and four different MRI markers of cerebral atrophy (parenchymal fraction, T2 lesion load, ventricular fraction and T1 lesion load) [57]. Interestingly, a study of CSF NF-L levels (not antibodies) also correlated with clinical markers of disease progression [91]. Animal studies related to these clinical observations suggest that autoimmunity to neurofilaments contribute to the pathogenesis of MS [60,61,92]. For example, following immunization with NF-L protein in ABH mice, animals developed spastic paraparesis concurrent with spinal cord axonal degeneration [60]. The mice developed a pro-inflammatory T-cell response, and importantly, they also developed antibodies to NF-L and IgG deposits within axons of spinal cord lesions [60]. In contrast to MOG-EAE, this NF-L EAE model showed a greater degree of spastic paraparesis, predominantly dorsal column and gray matter axonal degeneration as well as empty myelin sheaths [61]. Interestingly, like myelin proteins, neuronal proteins including NF-L are phagocytosed by human microglia in vitro and within MS plaques [93]. Taken together, these data indicate that autoimmunity to neurofilaments, and in particular, antibodies to neurofilaments, contribute to the pathogenesis of EAE, and potentially MS [61] (Figure 1). In a separate study, antibodies from the sera of MS patients were tested for immunoreactivity to oligodendrocyte, astrocyte and neuronal cell lines. MS patients showed increased immunoreactivity to all three cell lines compared to controls. However, only in the neuronal cell line (SK-N-SH), was there significant binding using sera from SPMS patients compared to RMS, benign MS and HCs [94].

Several groups have used an unbiased proteomics approach to identify putative autoantigens in MS patients [55,58,59,95]. For example, MS IgG was used to probe the glycoprotein fraction of human myelin purified by lectin affinity chromatography [55,58,95]. Proteins immunoreactive with MS IgG were identified by two-dimensional gel electrophoresis followed by mass spectroscopy. These studies identified immunoreactivity to two proteins: neurofascin and contactin-2/TAG-1 (transiently expressed axonal glycoprotein 1, the rat orthologue of contactin-2) [55,58,95]. Immunoreactivity to neurofascin was highest in a modest number of sera from chronic progressive MS patients [58]. MS IgG immunoreacted with two distinct isoforms of neurofascin: neurofascin 155 (an oligodendrocyte specific isoform) and neurofascin 186 (a neuronal form concentrated in axons at nodes of Ranvier) [58]. Application of anti-neurofascin antibodies to hippocampal slice cultures inhibited axonal conduction [58]. Following induction of experimental allergic encephalomyelitis (EAE) with MOG-specific T-cells, the addition of anti-neurofascin antibodies worsened clinical disease [58]. Anti-neurofascin antibodies bound to nodes of Ranvier, resulting in complement deposition and axonal injury. Taken together, these data indicate antibodies that target neuronal antigens are pathogenic and contribute to neurodegeneration [58,96] (Figure 1).

Most recently, IgG from MS patients was used in immunoprecipitation reactions of CNS membrane expressed proteins to identify putative autoantigens [59]. Following immunoprecipitation, two-dimensional electrophoresis of the eluent proteins in tandem with Western blot analyses (using MS IgG) and matrix-assisted laser desorption mass spectrometry identified the protein KIR4.1, a glial potassium channel [59]. Remarkably, 186/397 (46.9%) of MS patients were immunoreactive for KIR4.1 compared to 3/329 persons with OND (0.9%) and none of the 59 HCs. Importantly, MS antibodies bound glial cells in human brain sections and the immunodominant epitope (AA 83-120) was found to overlap one of two extracellular loops of KIR4.1 (AA 90-114). Infusions of anti-KIR4.1 antibodies with human complement into the cisterna magna of mice showed loss of KIR4.1 expression and activation of complement [59]. Taken together, these data suggest that the antibodies to the non-myelin antigen KIR4.1 may be a biomarker for and contribute to the pathogenesis of MS [59] (Figure 1).

![Figure 1: Potential contribution of antibodies to neurodegeneration in MS](image-url)
hnRNP A1 nucleocytoplasmic transport.
(A) Under normal conditions, hnRNP A1 (A1) binds transportin (Trn) via its M9 nucleocytoplasmic transport sequence; spastin RNA binds RNA binding domains (RBD) and upon RanGTP binding to Trn, the complex is transported through the nuclear pore to the cytoplasm (cyto). (B1) spastin and RanGTP are released into the cytoplasm, RanGTP is converted to RanGDP and hnRNP A1 and transportin return to the nucleus (nuc). The photomicrograph of SK-N-SH neurons shows that the vast majority of hnRNP A1 (green staining) is in the nucleus [118]. (B2) Under pathologic conditions when anti-M9 antibodies are present in neurons, hnRNP A1 transport from the cytoplasm to the nucleus is inhibited, thus hnRNP A1 is present equally in both the nucleus and cytoplasm. This may result in abnormal metabolism or transport of spastin and inhibition of binding of hnRNP A1 to Trn because of steric hindrance of the anti-M9 antibodies. The photomicrograph shows hnRNP A1 staining in the nucleus and cytoplasm, as well as fluorescently labeled anti-M9 antibodies (red) present in the neuronal cytoplasm [118].

Similar to the studies above, our laboratory (more than a decade ago) utilized an unbiased proteomics approach to test the hypothesis that antibodies isolated from patients with immune mediated neurological disease would immunoreact with CNS neuronal antigens [97]. We utilized a human neuron preparation taken at autopsy that is used to identify neuronal antigens in paraneoplastic syndromes [97-100]. The model we chose to examine was human T-lymphotrophic virus type 1 (HTLV-1) associated myelopathy/tropical spastic paraparesis (HAM/TSP) because it is similar pathologically, immunologically and clinically to progressive forms of MS [2,7,101-103]. Specifically, neuronal proteins isolated from human brain were separated by two-dimensional electrophoresis and transferred to membranes for Western blotting. We isolated IgG from HAM/TSP patients and used it to probe the Western blots. Following isolation and purification of the protein that immunoreacted with HAM/TSP IgG, matrix-assisted laser desorption mass spectrometry identified the target protein as heterogeneous nuclear ribonucleoprotein A1 (hnRNP A1) [97]. Importantly, an HTLV-1-tax monoclonal antibody showed cross-reactivity with human neurons and hnRNP A1, indicative of molecular mimicry between the two proteins [97,102-104]. hnRNP A1 is an RNA binding protein that is overexpressed in large neurons, whose primary function it to transport mature mRNA from the nucleus to the cytoplasm [97,102,105,106].

In contrast to HCs, all HAM/TSP patients tested immunoreacted with hnRNP A1 and transportin return to the nucleus (nuc). The photomicrograph of SK-N-SH neurons shows that the vast majority of hnRNP A1 (green staining) is in the nucleus [118]. (B2) Under pathologic conditions when anti-M9 antibodies are present in neurons, hnRNP A1 transport from the cytoplasm to the nucleus is inhibited, thus hnRNP A1 is present equally in both the nucleus and cytoplasm. This may result in abnormal metabolism or transport of spastin and inhibition of binding of hnRNP A1 to Trn because of steric hindrance of the anti-M9 antibodies. The photomicrograph shows hnRNP A1 staining in the nucleus and cytoplasm, as well as fluorescently labeled anti-M9 antibodies (red) present in the neuronal cytoplasm [118].

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Figure 2: hnRNP A1 nucleocytoplasmic transport.
(A) Under normal conditions, hnRNP A1 (A1) binds transportin (Trn) via its M9 nucleocytoplasmic transport sequence; spastin RNA binds RNA binding domains (RBD) and upon RanGTP binding to Trn, the complex is transported through the nuclear pore to the cytoplasm (cyto). (B1) spastin and RanGTP are released into the cytoplasm, RanGTP is converted to RanGDP and hnRNP A1 and transportin return to the nucleus (nuc). The photomicrograph of SK-N-SH neurons shows that the vast majority of hnRNP A1 (green staining) is in the nucleus [118]. (B2) Under pathologic conditions when anti-M9 antibodies are present in neurons, hnRNP A1 transport from the cytoplasm to the nucleus is inhibited, thus hnRNP A1 is present equally in both the nucleus and cytoplasm. This may result in abnormal metabolism or transport of spastin and inhibition of binding of hnRNP A1 to Trn because of steric hindrance of the anti-M9 antibodies. The photomicrograph shows hnRNP A1 staining in the nucleus and cytoplasm, as well as fluorescently labeled anti-M9 antibodies (red) present in the neuronal cytoplasm [118].
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Table 1: A sampling of antibody studies in MS.

### i. Myelin:

| Reference                  | MS/CIS | Controls | Serum | CSF | Antigen/technology | Primary results |
|----------------------------|--------|----------|-------|-----|--------------------|-----------------|
| Lisak et al., 1975 [63]    | 41     | 5 ALS; 16 OND (GBS, SSPE); 22 HC | IgG   | ND  | IMF of myelin in monkey or guinea pig spinal cord. All groups reacted with higher titers than HC. ALS showed greatest immunoreactivity. |
| Panitch et al., 1980 [64]  | 48     | 30 SSPE; 12 OND | ND    | IgG | MBP. Solid phase RIA. |                |
| Gorny et al., 1983 [65]    | 18     | 13 SSPE; 22 OND; 7 neurotic | ND    | IgG | MBP. RIA. |                |
| Waigl and Gorny, 1983 [66] | 40     | 40 neurotic | ND    | IgG | MBP, MAG. RIA. |                |
| Xiao et al., 1991 [67]     | 30     | 30 OND; 30 HA | ND    | IgG | MOG. ELISA. MS (23%); OND (10%); HA (3%) |                |
| Reinl et al., 1999 [68]    | 130    | 32 OND; 30 OND; 10 RA | IgG   | IgG | MBP. MOG. WB, ELISA. | No differences between groups by ELISA. WB highest in OIND; differences between groups not in favor of MS. |
| Karni et al., 1999 [69]    | 33 sera 31 CSF | Sera: 31 OND; 28 HC; CSF: 28 OND; 31 HC | IgG, IgM, IgA | IgG, IgM, IgA | MBP, MOG, ELISA. CSF: Abs to MOG, MBP elevated in MS & OND vs. HC. Frequency higher to MOG in MS & OND (not to MBP). Sera: titters elevated in MS vs. ONDs & HC, but frequency similar between groups. |
| Berger et al., 2003 [70]   | 103 CIS OCB (+) | None | IgM  | ND  | MBP. MOG. WB. MOG/MBP: +/+ (21%); +/− (38%); +/− (41%); 95% of MOG/MBP +/+ had relapse & predicted RRMS (=100%) |
| Lampasona et al., 2004 [71]| 87     | 12 EC, 47 HC | IgG, IgM | ND  | MBP, WB, RBD | No difference between groups. |
| Mantegazza et al., 2004 [72]| 262 (175 RR; 44 SP; 43 PP) | 131 OND 307 HC | IgG | IgG | MOG (extracellular domain). ELISA, WB. | CSF: no differences. Sera: MS (14%); OND (14%); HC (6%). Not specific for MS. CPMS: titer correlates with severity |
| Lim et al., 2005 [73]      | 47 CIS | None | IgG, IgM | ND  | MBP. MOG. WB. | Abs to MBP/MOG did not predict CDMS |
| Lalite et al., 2006 [74]   | 92 (35 RR; 33 SP; 24 PP); 36 CIS | 37 HC | IgG | ND  | MOG (native in transfected human cells) | Significant differences between CIS, RR, SP vs. HC, but not PP. |
| Rauer et al., 2006 [75]    | 45 CIS | 56 HC | IgM | ND  | MBP. MOG. WB. | No increase risk for CDMS. Ab (+) patients developed earlier relapses. |
| Khali et al., 2006 [76]    | 28    | 20 HC | IgG, IgM, IgA | ND  | MOG. ELISA. | IgM not significant. IgG and IgA significant. High degree of value overlaps between groups. |
| Kuhle et al., 2007 [77]    | 462 CIS | None | IgG, IgM | ND  | MBP. MOG. WB. | Risk of CDMS not influenced by any combination of positive Abs. |
| Menge et al., 2007 [78]    | 37 (17 RR; 10 SP; 10 PP) | 13 HC | IgG | ND  | rhMOG ELISA | No differences |
| Greene et al., 2007 [79]   | 31 CIS | None | IgM | ND  | MBP. MOG. WB. | MOG/MBP: +/+ & +/- greater risk of CDMS than +/- |
| Tomsa et al., 2007 [80]    | 51 CIS | None | IgG, IgM | ND  | MBP. MOG. WB. | Any positive Ab predicted CDMS by Poser criteria, not McDonald criteria. |
| Pittock et al., 2007 [81]  | 72 (12 pl; 43 pl; 17 plii) | None | IgG, IgM | ND  | MOG ELISA, WB. | No association with CDMS. |
| Wang et al., 2008 [82]     | 126    | 252 HC | IgG, IgM | ND  | MOG. EBNA. ELISA. | 2X increase of MS, but no association after adjustment for EBNA Abs. |
| Belgorouf et al., 2007 [83]| 26    | 22 OND; 11 HC | IgG | ND  | MBP. MOG. ELISA. | MOG & MBP: Significant differences vs. HC, not OND. Only Abs to MBP 43-48, 146-170 distinguished MS from OND. |
| Hedegaard et al., 2009 [84]| 17    | 17 HC | IgG | ND  | MBP microsphere. | No differences. |
| Chan et al., 2010 [85]     | 25 patients prior to CIS | 21 HC | IgG, IgM | ND  | Linear MBP. Linear and native MOG. | No association with CIS development. |
| Tewari et al., 2012 [86]   | 77 (37 RR, 27 SP; 13 PP) | 26 OND; 9 OIND | IgG | IgG | Myelin | No differences |

### II. Non-myelin:

| Reference                  | Controls | Serum | CSF | Antigen/technology | Primary results |
|----------------------------|----------|-------|-----|--------------------|-----------------|
| Rawes et al., 1997 [87]    | 20       | 17 OND, 13 HC | IgG | IgG | Axolotl neural enriched fraction (AEN) | Serum & CSF: significant differences in mean absorbance in MS compared to OND, HC. No correlation with myelin Ag |
| Sadatipour et al., 1999 [88]| 70 (33 RR; 21 SP; 16 PP) | 41 OND, 38 HC | Poly-valent Ig | ND  | Gangliosides GM1, GM3, GD1a, GD1b, GD3 | Significant differences in GM3: PP, SP compared to RRMS, OND, and HC |
| Silber et al., 2002 [89]   | 67 (39 RR; 18 SP; 10 PP) | 40 OND; 21 OIND, 12 HC | IgG | IgG | NF-L, NF-H, tubulin | Anti-NF-L antibodies significantly elevated in PPMS and SPMS compared to controls; correlated with EDSS. |
| Eikelenbom et al., 2003 [90]| 51 MS; 21 R; 20 SP; 10 PP | None | ND  | IgG | NF-L, NF-H | Anti-NF-L IgG index correlated with parenchymal fraction, T2 lesion load, T1 lesion load & ventricular fraction |
| Lilly et al., 2004 [91]    | 58 (35 RR (9 benign); 23 SP) | 12 HC 16 OND | IgG, IgM | ND  | SK-N-SH neurons Oligodendrocyte precursors cell lines | Only SK-N-SH cells showed differential response between SP (75%) and RR (25%). No differences in OPCs. |
Because of the similarities between HAM/TSP and progressive forms of MS, we hypothesized that antibodies isolated from MS patients would also immunoreact with hnRNP A1 [7] (Figure 1). This was found to be true. IgG isolated from MS patients preferentially immunoreacted with CNS neurons compared to systemic organs [7]. Further, MS IgG immunoreacted with hnRNP A1 and like HAM/TSP IgG, with the same epitope contained within M9 [7]. 37/37 MS patients reacted with hnRNP A1-M9 in contrast to HC (n=8) and Alzheimer’s patients (n=5, a control for neurodegenerative disease) [7]. CSF samples also immunoreacted with hnRNP A1-M9 and other groups have independently verified that HAM/TSP and MS IgG (isolated from CSF) react with hnRNP A1 [7, 111-113]. Clinically, approximately 90% of the MS patients tested had evidence of corticospinal dysfunction such as paraparesis, hyperreflexia or extensor plantar responses [7]. Next, we performed a series of experiments designed to test whether anti-hnRNP A1-M9 antibodies would alter hnRNP A1 function and contribute to neurodegeneration. M9 acts as both a nuclear export sequence (NES) and nuclear localization sequence (NLS) and is required for the transport of mRNA from the nucleus to the cytoplasm [105, 108] (Figure 2). Nucleocytoplasmic transport occurs when mRNA binds hnRNP A1 via its RNA binding domains and a protein named transportin binds hnRNP A1 via M9. The complex binds RanGTP in the nucleus and the entire complex is transported through the nuclear pore to the cytoplasm [114]. Upon depositing mRNA in the cytoplasm, hnRNP A1 is transported back through the nuclear pore to the nucleus. In addition to mRNA nucleocytoplasmic transport, hnRNP A1 also plays a role in the regulation of mRNA transcription and translation [105, 106]. Upon exposure to anti-hnRNP A1-M9 antibodies in vitro, neurons showed evidence of neurodegeneration [7, 115]. Microarray analyses of the neurons compared to neurons exposed to control antibodies showed preferential expression of genes related to both hnRNP A1 function and the clinical phenotype of progressive MS patients. Specifically, the spinal paraplegia genes (SPGs) were down regulated [7]. Mutations in SPGs cause hereditary spastic paraparesis (HSP), genetic disorders clinically indistinguishable from progressive MS [6, 116, 117]. Importantly, SPG antibodies were also found to be down regulated in CNS neurons purified from MS patients compared to neurons from control brains [7]. In separate in vitro experiments, anti-M9 antibodies were found to enter neurons by utilizing clathrin-mediated endocytosis, a mechanism identical to antibodies isolated from ALS patients [118, 119]. Neuronal cells exposed to the anti-M9 antibodies caused apoptosis and reduction in cell viability [120, 121]. In addition, anti-M9 antibodies have been shown to play a role in microtubule stability in neurons [121], and have been shown to play a role in microtubule stability in neurons [121]. In turn, to normal synaptic growth and transmission [124]. In addition, anti-M9 antibodies have been shown to play a role in microtubule stability in neurons [121]. In turn, to normal synaptic growth and transmission [124]. In addition, anti-M9 antibodies have been shown to play a role in microtubule stability in neurons [121]. In turn, to normal synaptic growth and transmission [124]. In addition, anti-M9 antibodies have been shown to play a role in microtubule stability in neurons [121].
Interestingly, immunization with sulfatide in a PLP-GM1 and asialo-GM1 showed preferentially immunoreactivity [128]. When comparing SPMS to OND, ethanolamine, lysophosphatidyl ethanolamine, sphingomyelin and 5α-cholestan-15-one, oxidized phosphatidylcholine, phosphatidyl increased immunoreactivity to lipids containing sulfatide, 3β-hydroxy-specific lipid profiles [128]. Comparing MS to OND patients, there was [95] (Table 1).

When lipid microarrays were analyzed using myelin and non-myelin lipids, CSF from MS patients showed preferential immunoreactivity to specific lipid profiles [128]. Comparing MS to OND patients, there was increased immunoreactivity to lipids containing sulfatide, 3β-hydroxy-5α-cholestan-15-one, oxidized phosphatidylcholine, phosphatidyl ethanolamine, lysophosphatidyl ethanolamine, sphingomyelin and asialo-GM1 (a ganglioside) [128]. When comparing SPMS to OND, GM1 and asialo-GM1 showed preferentially immunoreactivity [128]. Interestingly, immunization with sulfatide in a PLP, pattern 2 (antibody/complement mediated) type MS pathologies. In these studies, differential autoantibody immunoreactivities were found to myelin (MOG, PLP), non-myelin (neurofilament 160kDa) and lipid targets. Administration of some of these lipids augmented MOG[15-55] EAE [130].

### Conclusion

MS is a complex, multifactorial disease. Data suggests MS is a two-phase disease [2,131-133]. The early phase is predominantly inflammatory/demyelinating and the secondary/progressive phase is neurodegenerative. However, many studies show that neuronal and axonal damage are present in early phases of MS, suggesting mechanisms of neurodegeneration contribute to MS pathogenesis throughout the disease. Recent studies have unveiled that immune responses to non-myelin target antigens contribute to neurodegeneration and the pathogenesis of MS. Considering there are no effective therapies for progressive forms of MS, a comprehensive understanding of antibody-mediated mechanisms of neurodegeneration in MS should lead to novel therapeutic agents to treat it, and thus, reduce disability.

### Potential Conflicts of Interest

Drs. Michael Levin and Sangmin Lee have a patent pending titled "Biomarker for neurodegeneration in neurological disease".

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