Characterizing the Mechanisms of Progression in Multiple Sclerosis

Evidence and New Hypotheses for Future Directions

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Major advancements have been achieved in our ability to diagnose multiple sclerosis (MS) and to commence treatment intervention with agents that can favorably affect the disease course. Although MS exacerbations and the emergence of disability constitute the more conspicuous aspects of the disease process, evidence has confirmed that most of the disease occurs on a constitutive and occult basis. Disease-modifying therapies appear to be modest in the magnitude of their treatment effects, particularly in the progressive stage of the disease. Therapeutic strategies currently used for MS primarily target the inflammatory cascade. Several potential mechanisms appear to be involved in the progression of MS. Characterizing these mechanisms will result in a better understanding of the various forms of the disorder and how to effectively treat its clinical manifestations. It is our objective within this 2-part series on progression in MS to offer both evidence-based observations and hypothesis-driven expert perspectives on what constitutes the cause of progression in MS. We have chosen areas of inquiry that appear to have been most productive in helping us to better conceptualize the landscape of what MS looks like pathologically, immunologically, neuroscientifically, radiographically, and genetically. We have attempted to advance hypotheses focused on a deeper understanding of what contributes to the progression of this illness and to illustrate new technical capabilities that are catalyzing novel research initiatives targeted at achieving a more complete understanding of progression in MS.

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THE PATHOLOGIC MECHANISM OF PROGRESSION IN MULTIPLE SCLEROSIS

Relapse and Progression

Relapses and progression of disability are the 2 basic clinical phenomena of multiple sclerosis (MS). Relapses are considered to be the clinical expression of acute inflammatory demyelination in the central nervous system (CNS), whereas progression is considered to reflect chronic demyelination, gliosis, and axonal loss. Early in the disease, remission of symptoms is likely due to resolution of inflammation, channel redistribution, and remyelination; however, following recurrent attacks, axonal damage is more likely to occur, and axonal loss accumulates. Hence, the balance between injury and repair likely determines the progression of MS.

Recent reports have emphasized the importance of axonal degeneration in contributing to permanent neurologic deficits in patients with MS. The extent of axonal loss is highly variable, with axonal density within plaques ranging from 20% to 80% of that in the periplaque white matter.

Hypothesis, Evidence, Future Directions

We hypothesize that the accumulation of axonal destruction underlies clinical pro-
gression in patients with MS. Support for this contention derives from our understanding that inflammation correlates with the extent of axonal transection in active MS lesions. However, the magnitude of axonal loss in chronic lesions suggests that mechanisms other than inflammatory demyelination may contribute to axonal damage at later stages of the disease. Axons in MS lesions may be destroyed in 2 different ways. During acute demyelination, axons are likely damaged owing to inflammatory mediators, such as proteases, cytokines, and free radicals. An association between the number of CD8 T cells and the extent of axonal damage has been reported.

A CD8 major histocompatibility complex (MHC) class I–mediated pathway of axon destruction has been suggested from experimental studies. Inducible nitric oxide may also mediate axon damage. This acute phase of massive axonal injury, however, lasts only for a few days to weeks. In contrast, axonal degeneration continues in silent inactive plaques. Although merely a few axons are destroyed at a given time point, the accumulation of their destruction can contribute to progression of disability. Chronically demyelinated axons may degenerate owing to the lack of trophic support from myelin and oligodendrocytes. Mice that lack certain myelin proteins (myelin-associated glycoprotein [MAG] and photolipid protein [PLP]) demonstrate late-onset axonal disease, and there is evidence of an increased incidence of wallerian degeneration in MAG-deficient mice.

Axonal injury and loss of MS lesions have major clinical consequences for the patient. Clinical deficits induced by inflammation and demyelination are principally reversible, whereas functional loss due to axonal degeneration appears to be permanent. Although the CNS has a large reserve capacity, irreversible structural damage accumulates in MS brains. Although substantial damage can be sustained, permanent clinical deficits appear to coincide with a time when the functional reserve capacity is exhausted. Therefore, the need to develop axon-protective therapy for MS will be crucial to our attempt to slow disease progression (see part 2 ).

THE IMMUNOLOGIC FEATURES OF PROGRESSION IN MS

Role of T Cells in Progression

The clinical characteristics that separate secondary progressive MS from relapsing-remitting disease are better defined than the immunologic differences. It has been suggested that priming of myelin-reactive T cells occurs as part of the disease process in MS. Primed T cells reactive to myelin antigens may develop a phenotype, making them more resistant to regulatory processes such as programmed cell death. One might expect that these T-cell clones would retain effector functions such as interferon γ secretion but be resistant to the regulatory effects of various therapeutic interventions. It is possible that this resistance to programmed cell death could be an explanation of why interventions such as anti-CD4 therapy were ineffective in patients with MS. Studies on the immune response in patients who are receiving anti-CD4 therapy have suggested that naive cells, rather than differentiated Th1-like cells, are eliminated.

Hypothesis, Evidence, and Future Directions

One could hypothesize that a more inflammatory profile of myelin-reactive T cells correlates with disease progression. Increased CD40 ligand expression on T cells from patients with progressive MS has resulted in increased interleukin (IL) 12 production. Increased responses to myelin peptides showed a correlation with disability. A correlation between tumor necrosis factor α (TNF-α)–producing CD4 T cells and changes in T2 lesion load has also been reported.

Both CD8 and CD4 T cells contribute to the cellular infiltrate of demyelinating lesions in patients who have MS with evidence of CD8 T-cell enrichment and clonal expansion. Some of these brain-infiltrating CD8 T cells have persisted in the cerebrospinal fluid or blood for longer than 5 years, suggesting that they may play a role in disease progression. The CNS-reactive CD8 T-cell responses have been demonstrated in these patients. Recent technical advancements in flow cytometric assays allow evaluation of antigen-specific CD4 and CD8 T-cell proliferative responses in patients with MS. These studies demonstrate that CNS-reactive T cells are not restricted to the CD4 T-cell subset. In fact, autoreactive HLA antigen class I–restricted CD8 T-cell responses are widely prevalent in MS. A higher prevalence of autoreactive CD8 T-cell responses was noted in patients with relapsing-remitting MS compared with other MS subtypes.

The CNS-specific T-cell responses are found in patients with MS and healthy subjects. However, the functional attributes of these cells are distinct in the 2 groups, in which CNS-targeted T cells from patients are thought to be more differentiated compared with those from healthy subjects, suggesting that the cells may have experienced self-antigen in vivo. When CD4 and CD8 T cells were specifically evaluated for their functional profiles, differences were noted in both subsets of cells. Although autoreactive CD4 T cells appeared to exhibit a more T helper (Th1)–type profile, autoreactive CD8 T cells showed a mixed functional profile in which higher interferon γ and chemokine receptor 3 expression was accompanied by higher IL-10 expression in patients with MS.

Similar to regulatory subpopulations of CD4 T cells, CD8 T cells have also been implicated as regulatory cells in both experimental autoimmune encephalomyelitis (EAE) and MS. It is possible that the progression of disease in MS depends on a relative lack of regulatory T-cell function. In keeping with this hypothesis, a deficient CD8 T-cell response to glatiramer acetate (Copaxone, Teva Neuroscience, Kansas City, Mo) was found in patients with MS but not in healthy subjects. Although patients with MS have widespread, CNS-specific CD8 T-cell responses, glatiramer acetate therapy can restore glatiramer acetate–specific CD8 responses to the levels found in healthy subjects. A complex pathogenic and regulatory balance may exist within the CD8 T-cell subset. These findings strengthen the need for defining the role of CD8 T cells in disease progression.
Role of B Cells in Progression

The concept that autoantigens can drive B-cell clonal expansion and generate an autoantibody pool that contributes to autoimmunity has been demonstrated in other autoimmune diseases. However, it has been observed that if the B-cell–monocyte ratio is high, progression of MS is more likely to occur. In the EAE model, a role of B cells in the recovery from inflammatory demyelination has also been hypothesized.

Hypothesis, Evidence, and Future Directions

We hypothesize at least 3 different roles that a B cell might play in the progression of MS. The first is through B-cell clonal expansion. If new antigens have been exposed through ongoing myelin damage, B cells that recognize these newly exposed antigens in the CNS may undergo clonal expansion and differentiation, resulting in a larger pool of antigen-presenting cells participating in the immune response. Second, if the patient has recently had an infection that generated a B-cell response in which the resultant antibody not only recognized the viral or bacterial components but also was cross-reactive with some antigen in the CNS, it is possible that such infections may lead to breakthrough disease by indirectly generating antibodies that are cross-reactive to self-antigens in the CNS. This concept is known as molecular mimicry and occurs in some infectious states, such as human T-cell lymphotrophic virus type 1. A third possibility relates to the process of immunoglobulin class switching that occurs in B cells. All B cells initially produce IgM, and at a certain point, they are induced to produce IgG instead. In several autoimmune states, the IgG component of the immunoglobulins contains the bulk of autoreactivity rather than the IgM component. This switch of self-reactive B cells from IgM to IgG producers could contribute to disease progression.

Each of the mechanisms by which B cells can contribute to progression in MS can potentially be prevented. For example, receptor editing is a phenomenon by which B cells that recognize self-antigens attempt to neutralize their autoreactive potential by replacing the light chain they are currently expressing with a newly rearranged one. It has been demonstrated that receptor editing occurs in B cells in the cerebrospinal fluid of patients with MS. Receptor editing should discourage further damage to the CNS tissue by autoantibody deposition. However, receptor editing could fail to prevent autoreactivity and instead generate a new antibody with greater self-antigen reactivity or reactivity to more than 1 self-antigen, which could lead to disease progression. In addition, one might be able to prevent B-cell–mediated pathogenesis by depleting the B cells altogether. This approach has led to suppression of autoimmunity in other diseases with known B-cell involvement.

Determinant (Epitope) Spreading

The terms determinant spreading and repertoire broadening describe the same phenomenon. The concept of epitope spreading emerged in the early 1990s to describe 2 phenomena: (1) diversity at the level of the T-cell receptor V gene (variable) use and (2) cellular and humoral immune response diversification from a single to numerous antigenic determinants. Epitope spreading is not necessarily a pathogenic immune response but may instead be required for the effective clearing of various infectious agents.

Hypothesis, Evidence, and Future Directions

Epitope spreading may contribute to the occurrence of disease exacerbations in patients who have MS with a relapsing-remitting phenotype. One group recently showed epitope spreading to overlapping PLP peptides in patients with a clinically isolated demyelinating syndrome. The same authors reported that HLA-DP–restricted epitopes may be recognized by initiating or early-driving clones at disease onset. We hypothesize, as these processes occur, that specific therapeutic interventions would be less effective and disease progression could occur.

Cytokine Effects on Progression

According to the TH paradigm, activated CD4 lymphocytes are categorized into TH1 or TH2 cells according to their cytokine profile. Although it is now recognized that activated helper CD8 T cells can also be categorized into TH cytotoxic 1 (T1) and T2 subsets (analogous to CD4 TH1 and TH2 cells, respectively), herein we will primarily focus on the role of CD4 TH subsets in progression of MS.

The adaptive immune system induces T cells to change from a naïve phenotype to either effector cells or memory cells. The TH1/TH2 phenotype reflects the functional capabilities following T-cell activation. In the human immune system, TH1 cells secrete interferon γ, TNF-β, and IL-2, whereas TH2 cells produce IL-4, IL-5, IL-6, and IL-13. The role of TH1 phenotypes (eg, TH1p, TH1o) in human diseases has yet to be clearly defined. However, cytokines associated with the TH1 response, such as IL-12 and TNF-α, appear to correlate with disease progression.

Hypothesis, Evidence, and Future Directions

We hypothesize that T helper cells of a TH1 cytokine phenotype contribute to disease progression in MS, whereas self-antigen–specific TH2 cells prevent CNS autoimmune disease. Intracellular cytokine staining confirmed that peripheral blood mononuclear cells from patients with progressive MS express more IL-12 on activation than those from healthy controls. Another TH1 cytokine, interferon γ, is a potent inducer of surface MHC class II expression on a variety of antigen-presenting cells. The clinical significance of this cytokine in MS pathogenesis was demonstrated when it was shown that the systemic administration of interferon γ caused exacerbations in patients with progressive MS.

Numerous approved and experimental MS pharmacotherapies have been shown to promote a shift or deviation to a TH2 cytokine profile. Unfortunately, administration of a myelin basic protein peptide (amino acids 83-99) designed as an altered peptide ligand to induce a...
T_{H}2 cytokine profile in MS was followed by disease exacerbations in several patients. However, another study using this altered peptide ligand did not show disease worsening, but some patients experienced adverse allergic responses.

The view that T_{H}1 cytokines are proinflammatory and T_{H}2 cytokines anti-inflammatory may be oversimplified. Although T_{H}1 cytokines promote the activation of antigen-presenting cells and the clearance of intracellular pathogens, T_{H}2 cytokines support antibody class switching in mice, promote the elimination of blood-borne pathogens, and may contribute to autoimmune disease in humans. Finally, cytokines such as IL-17 and IL-23, which are gaining a more prominent role in EAE pathogenesis, will need to be studied for their role in MS disease progression.

Lymphocyte Trafficking and Progression

Once T cells are activated, these lymphocytes travel through blood vessels in the brain and spinal cord and are captured by molecules on the blood vessel wall that bind to counterreceptors on the activated lymphocyte. After they are firmly bound to the cerebrovascular endothelium, these cells can then elaborate matrix metalloproteinases capable of digesting collagen type IV and fibronectin, which facilitates transmigration.

Hypothesis, Evidence, and Future Directions

Each step in the process of transendothelial trafficking represents a potential checkpoint. For example, the capture and binding of lymphocytes to the blood vessel wall can be blocked by drugs that interfere with the adhesion molecules on the lymphocyte and endothelial wall, including monoclonal antibodies to α4-integrin. The process of transmigration can be stopped by statins that block the addition of lipid moieties on certain molecules in the membrane that are critical for maintaining the shape of the T cell. Statins block the preylation of ras homology protein molecules on the cell surface that are linked to the migration of lymphocytes into the brain.

Immunologists hypothesized in the early 1990s that lymphocytes used specific addresses to home to targets like the CNS. By identifying the address used to send lymphocytes to a particular organ, it was argued that blocking the particular molecule with an “address-like signature” would thus abolish pathologic homing but would leave lymphocytes free to move elsewhere. One type of molecule, termed α4-integrin, on T lymphocytes allows T cells to recognize vascular cellular adhesion molecule 1 in the brain endothelium. The α4-integrin that recognizes vascular cellular adhesion molecule 1 is an essential step required for the capture of lymphocytes. Vascular cellular adhesion molecule 1 usually is not expressed at high levels in blood vessels in the brain, although in animal models and in MS its expression is increased. Administration of α4-integrin antibodies in EAE reversed the paralytic disease and blocked encephalitogenic T-cell clones from entering the brain.

Antibody to α4-integrin was successful in phase 2 MS clinical trials, in which it reduced the relapse rate by 50% and diminished the number of new gadolinium-enhancing lesions in a 6-month clinical trial by nearly 90%. The year 1 results from 2 phase 3 (class I) studies on the use of natalizumab in relapsing MS have been reported. The first (AFFIRM) compared natalizumab with placebo, whereas the second (SENTINEL) compared weekly intramuscular interferon beta-1a (Avonex, Biogen Idec, Cambridge, Mass) and placebo with intramuscular interferon beta-1a and natalizumab. Both investigations show highly statistically significant beneficial effects of natalizumab on clinical (relapses) and radiographic measures of disease activity. The Food and Drug Administration approved natalizumab on November 23, 2004, for the treatment of relapsing forms of MS; yet it was later withdrawn because of the appearance of progressive multifocal leukoencephalopathy in 2 patients in the SENTINEL trial (Food and Drug Administration Web site: http://www.fda.gov/cder/drug/advisory/natalizumab.htm).

THE NEUROSCIENCE OF PROGRESSION IN MS

Role of Astrocytes in Progression

In new MS lesions, astrocytes proliferate and become hypertrophic. In chronic lesions, astrogial scarring can form an obstacle that prevents repair. A primary dysfunction of astrocytes in MS might be involved in lesion formation and progression of disability. A loss of astrocytic β_2-adrenergic receptors in MS might explain many of the pathologic changes of the disease and play a role in both inflammation-mediated injury and progressive neurodegeneration. Activation of β_2-adrenergic receptors by norepinephrine increases intracellular levels of cyclic adenosine monophosphate (cAMP), which controls many astrocytic functions.

Hypothesis, Evidence, and Future Directions

We hypothesize that lack of β_2-adrenergic receptors may allow astrocytes to express adhesion, MHC class II, and B7 costimulatory molecules and to act as antigen-presenting cells that can initiate inflammatory reactions. During inflammation, lymphocytes, microglia, and macrophages release excessive amounts of glutamate. The lack of β_2-adrenergic receptors on astrocytes may impair glutamate uptake and contribute to excitotoxic damage of oligodendrocytes through overactivation of AMPA (α-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid) receptors. The receptor defect may also facilitate the release from astrocytes of proinflammatory cytokines such as TNF-α, which is involved in myelin and oligodendrocyte destruction, and result in the expression of nitric oxide synthase.

Evidence is mounting that axons and oligodendrocytes use astrocyte-derived lactate as an energy source. Lactate is generated from astrocytic glycogenolysis that is stimulated by norepinephrine via β_2-adrenergic receptor activation. The lack of astrocytic β_2-adrenergic receptors in MS might prevent an adequate lactate supply to axons, especially in situations of increased neuronal activity. Intracellular cAMP in astrocytes also stimulates the production of various trophic factors, including neuregulin, nerve growth factor, and brain-derived growth factor.
regulin, which is a survival factor for oligodendrocytes, has been studied in astrocytes of patients with MS and was found to be reduced in active and chronic lesions.

**Potential Role of Sodium Channels in Progressive MS**

Although axonal injury is frequent in early stages of MS and contributes to the acquisition of nonremitting deficits, evidence suggests that excitotoxicity is not a principal trigger. It has been firmly established that calcium-mediated injury can lead to persistent axonal dysfunction and axonal degeneration within CNS white matter. Biophysical evidence indicates, as shown in the figure, that following a spectrum of insults, reverse sodium-calcium exchange, triggered by sodium influx via voltage-gated sodium channels, can produce injurious sustained calcium influx. Pharmacologic block of the sodium-calcium exchanger and of sodium channels is protective, preventing axonal degeneration in response to a spectrum of experimental models of axonal injury.

On the basis of pathologic examination of MS tissue, it has been suggested that hypoxialike tissue injury is a component of MS lesions. Nitric oxide is present at increased concentrations within MS lesions and interferes with mitochondrial function. This observation suggests a role for energy failure in producing axonal injury in MS. Electrically active axons were found to be particularly sensitive to the damaging effects of nitric oxide. It has been shown that sodium channel blockers prevent nitric oxide–induced injury of CNS axons, suggesting that inflammatory events (which are associated with nitric oxide production) in MS can also trigger a component of the tissue injury cascade in MS (Figure). Irrespective of the trigger, operation of this axon-damaging cascade in MS requires colocalization of sodium channels and the sodium-calcium exchanger in close proximity along axons that are destined to degenerate. This link was shown to be related to the coexpression of the voltage-gated sodium channel, together with the sodium-calcium exchanger, in injured CNS axons (but not in uninjured axons) in both EAE and MS.

The in vitro studies that demonstrated this axon-damaging cascade have recently been extended by an in vivo study in which the sodium channel blocker phenytoin was shown to have a neuroprotective effect in pro-
gressive EAE. In that study, phenytoin decreased the degree of axonal degeneration, maintained action potential conduction, and substantially improved clinical outcome.

**Hypothesis, Evidence, and Future Directions**

On the basis of these findings, it has been hypothesized that sodium channel blockade may have a neuroprotective effect, preserving axonal integrity and function and thereby preventing nonremitting deficits in MS. The putative neuroprotective mechanism of action of these drugs (which appear to target molecules located within neurons) makes them ideal candidates for adjunctive therapy (see part 2).

**CNS Repair and Regeneration**

Progression in MS is likely the result of impaired axonal regeneration following immune-mediated injury. Understanding the mechanisms of how axonal regeneration is inhibited in the CNS has important clinical implications for MS. Three inhibitor proteins, neurite outgrowth inhibitor (Nogo), MAG, and oligodendrocyte myelin glycoprotein, inhibit CNS neural regeneration through the Nogo receptor and associated p75 neurotrophin receptor and leucine-rich repeat and immunoglobulin domain–containing Nogo receptor–interacting (LINGO) protein. In mice that underwent thoracic cord hemisection, those that were Nogo-A deficient demonstrated increased regrowth of axons after the traumatic injury. Both MAG and oligodendrocyte myelin glycoprotein also appear to inhibit axon regeneration through binding of the Nogo receptor complex. Once the Nogo receptor is activated, transmission of the signal is mediated by protein kinase C and cAMP. Interestingly, elevated levels of cAMP attenuate the ability of MAG to inhibit axon regeneration in vitro.

**Hypothesis, Evidence, and Future Directions**

On the basis of these studies, we hypothesize that cAMP levels might affect axonal regeneration following spinal cord injury. In mice in which the levels of cAMP were increased, axonal regeneration was significantly improved. Cytokines such as IL-6 are also increased in response to increased levels of cAMP. In addition, IL-6 appears to be effective in attenuating MAG inhibition of axon regeneration. Perhaps drugs such as phosphodiesterase inhibitors will be targeted to regulate cAMP levels and reduce MAG inhibition of axon degeneration in immune-mediated CNS injury. Increasing neurite outgrowth, reducing glial scar formation, and increasing functional recovery might influence disease progression in MS.

**THE NEURORADIOLOGIC FEATURES OF PROGRESSION IN MS**

**Neuroradiologic Detection of Tissue Injury in MS Progression**

Conventional magnetic resonance imaging (MRI) is widely used for diagnosing and monitoring MS; however, the correlation between conventional MRI and clinical findings of MS is still limited. Among the reasons for these radiologic and clinical discrepancies, a major role has been attributed to the low pathologic specificity of the abnormalities seen on conventional MRI studies and the inability of conventional MRI to quantify the extent of the damage of the normal-appearing tissue. In addition, lesion location itself is another variable that plays a significant role in determining the level of disability.

**Hypothesis, Evidence, and Future Directions**

We hypothesize that application of modern magnetic resonance–based techniques such as magnetization transfer MRI, diffusion tensor MRI, and magnetic resonance spectroscopy to the assessment of patients with MS has significantly changed the notion of MS as a demyelinating disease. First, axonal damage, which may be represented by either axonal loss or dysfunction, has been recognized as one of the main contributors to clinical worsening over time. This pathologic process is an early phenomenon in the course of MS; it has been detected even in patients at presentation with clinically isolated syndromes suggestive of MS. Second, widespread abnormalities, which go undetected when using conventional MRI, have been demonstrated in the normal-appearing white matter of patients with MS. Such abnormalities are more pronounced in patients with secondary and primary progressive MS and tend to worsen over time. Third, it has been shown that the gray matter is not spared by the disease process and likely contributes to some of the symptoms of the disease, such as cognitive impairment, mood disorders, and fatigue. Finally, the application of these magnetic resonance techniques is improving our ability to obtain precise estimates of the composition and severity of damaged structures, such as the optic nerves and the spinal cord.

In the case of axonal and neuronal damage, the factors that have traditionally been viewed as potentially able to limit the clinical impact of MS (ie, resolution of inflammation, remyelination, and redistribution of voltage-gated sodium-channels in persistently demyelinated axons) are all likely to have a limited role. Functional MRI studies have demonstrated cortical changes in patients with different disease courses. The relationship found between these changes and magnetic resonance measures of brain and cord damage suggests that brain plasticity might play a major adaptive role in limiting the functional consequences of MS-related widespread tissue damage.

**THE GENETICS OF PROGRESSION IN MS**

**Analysis of Gene Expression in MS**

The development of multiplex analysis of transcripts from MS tissues has advanced our understanding of the disease. These approaches to decipher the messenger RNA transcripts found at the site of MS lesions have revealed several targets for therapy, as well as increasing our awareness of the complexity of the disease. Large-scale transcriptional analysis of MS brain tissue has revealed that...
possible targets for therapy include elements of cholesterol metabolism, such as key enzymes involved in cholesterol synthesis, histamine receptors, and various cytokines including TNF, IL-15, IL-17, and osteopontin. Large-scale robotic sequencing of messenger RNA from complementary DNA libraries derived from MS brain plaques and gene microarray analysis of transcripts from MS lesions of various types have been performed by several groups.

A potential role for osteopontin (also known as Eta-1) in the progression of MS was identified. In the present study, more than 11,000 clones were sequenced from libraries prepared from brain plaques in patients with MS and controls. Elucidated were 423 genes, including 26 novel genes that were present only in MS plaques and absent in control material. Transcripts for αB-crystallin, an inducible heat shock protein localized in the myelin sheath and targeted by T cells in MS, were the most abundant transcripts unique to MS plaques. The next 5 most abundant transcripts included those for prostaglandin D synthase, prostatic binding protein, ribosomal protein L17, and osteopontin.

Hypothesis, Evidence, and Future Directions

We hypothesize that disease progression in MS is influenced by genetic and nongenetic factors. The genomic determinants of MS heterogeneity are most likely single-nucleotide polymorphisms. It is also important to recognize that the aggregate contribution of germline genetic variants to the disease course of a given patient with MS may be modest. This is highlighted by observations that the clinical expression of MS may be very different even between monoyzotic twin siblings who both have the disease. It is therefore likely that several postgermline events influence the clinical expression of MS.

Earlier studies have reported intrafamilial concordance for disease course, disease severity, and age at onset. The clinical course and severity of MS may also differ between ethnic groups. This phenotypic aggregation is due to genetic sharing. In EAE, it appears that MHC genes primarily influence penetrance, whereas other loci modulate specific phenotypes, such as topographic location of lesions in the brain or spinal cord, demyelination, and severity of inflammation. Similar interplay of genetic factors may apply to human disease.

To assess the state of genotype-phenotype research in MS, we have identified from the literature a set of gene polymorphisms that have been significantly associated with phenotypic end points. The list includes many reports and probably includes a few type I errors due to small sample sizes. In addition, series are retrospective, some phenotypic end points are questionable or not validated, and the confounding effects of drug treatment and/or stratification generally have not been considered. The effect of HLA genotypes (ie, both alleles at the HLA locus) on clinical phenotypes is particularly instructive.

In a mildly affected group of patients with MS, HLA-DRB1*1501 homozygotes were significantly less frequent compared with patients classified as having nonmild MS. When a more stringent definition of mild MS was applied in which disease duration of at least 15 years was imposed, no HLA-DRB1*1501 homozygotes were present in this subgroup. Furthermore, HLA-DRB1*1501 homozygotes were observed more frequently among patients with a severe disease course in contrast to patients classified as having nonsevere disease. The observed dose effect could conceivably result from a perturbation in the balance of TNF and IL-1 cytokines influenced by other genes in the HLA region, such as TNF. For example, HLA-DRB1*1501 haplotypes are associated with a TNF promoter polymorphism that modulates levels of expression of this proinflammatory cytokine.

The observation of an HLA genotypic effect on disease outcome is also consistent with a model of protection mediated by HLA-DRB1*1501-negative haplotypes.

THE FUTURE

The past few years have seen real progress in the development of laboratory and analytical approaches to study complex genetic disorders on a genome-wide scale and in defining the pathologic basis of demyelination. There is widespread enthusiasm that the deconstruction of the MS-prone genotype may lead to novel diagnostics and, more important, better therapeutic options for our patients. Unexpected overlap between genomic variations
associated with MS and other medical disorders might be uncovered, such as a role for APOE4 as a modifier in both Alzheimer disease and MS. The development of reliable and predictive genomic profiles will not be trivial because of experimental constraints and practical economical and ethical considerations.

Identification of genomic variants that predispose patients to a discrete phenotype might also reveal novel disease-associated biochemical pathways and new therapeutic targets. The demonstration of even a modest genetic effect of a known gene on the course of MS could represent a major therapeutic opportunity.

Table. Examples of Gene Variants That Have Been Associated With Multiple Sclerosis Phenotype

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<thead>
<tr>
<th>Gene or Locus</th>
<th>Chromosomal Location</th>
<th>Allele</th>
<th>Associate Phenotype</th>
<th>Source</th>
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<tbody>
<tr>
<td>GSTM1</td>
<td>1p13.3</td>
<td>Ile105</td>
<td>Severe disability</td>
<td>Mann et al&lt;sup&gt;85&lt;/sup&gt;</td>
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<tr>
<td>IL-1ra/IL-1β</td>
<td>2q14.2</td>
<td>allele 2 of IL-1β, allele 3 of IL-1ra</td>
<td>High protein expression and favorable prognosis</td>
<td>Schrijver et al&lt;sup&gt;86&lt;/sup&gt;, Kantarci et al&lt;sup&gt;87&lt;/sup&gt;</td>
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<tr>
<td></td>
<td></td>
<td>IL-1ra intron 4 VNTR</td>
<td>High protein expression and favorable prognosis</td>
<td>Sciacca et al&lt;sup&gt;88&lt;/sup&gt;, Feakes et al&lt;sup&gt;90&lt;/sup&gt;</td>
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<tr>
<td>CCR5</td>
<td>3p21-24</td>
<td>Δ32-base pair deletion</td>
<td>Age at onset was approximately 3 y later in patients carrying the deletion</td>
<td>Barcellos et al&lt;sup&gt;92&lt;/sup&gt;</td>
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<td></td>
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<td>Progression to disability was delayed in homozygotes and heterozygotes for the deletion</td>
<td>Kantor et al&lt;sup&gt;93&lt;/sup&gt;</td>
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<td></td>
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<td></td>
<td>Lower risk of recurrent disease activity</td>
<td>Sellebjerg et al&lt;sup&gt;94&lt;/sup&gt;</td>
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<td>Trend toward reduced frequency in PPMS</td>
<td>Haase et al&lt;sup&gt;95&lt;/sup&gt;</td>
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<td></td>
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<td></td>
<td>Trend toward smaller lesion burden</td>
<td>Schreiber et al&lt;sup&gt;96&lt;/sup&gt;</td>
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<td></td>
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<td>Patients with the wild-type 1284A genotype are less likely to have mild disease course and were at increased risk for a secondary-progressive clinical type</td>
<td>Caillier et al&lt;sup&gt;97&lt;/sup&gt;</td>
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<tr>
<td>OPN</td>
<td>4q21-q25</td>
<td>1284A→C</td>
<td>High protein expression and favorable prognosis</td>
<td>Sciacca et al&lt;sup&gt;88&lt;/sup&gt;, Feakes et al&lt;sup&gt;90&lt;/sup&gt;</td>
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<td>9583 G→A</td>
<td>Patients with the 9583 G/G genotype showed later disease onset</td>
<td>Niino et al&lt;sup&gt;91&lt;/sup&gt;</td>
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<td></td>
<td></td>
<td>Rs 4754, Rs 1126616, Rs 4660, Rs 1126772, Rs 1126859, Rs 9138, Rs 1126880, Rs 1126893</td>
<td>No association with disease severity</td>
<td>Hensiek et al&lt;sup&gt;92&lt;/sup&gt;</td>
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<tr>
<td>IL-4</td>
<td>5q31.1</td>
<td>VNTR B1</td>
<td>Late onset, late onset in homozygotes</td>
<td>Vandenbroeck et al&lt;sup&gt;93&lt;/sup&gt;, Kantarci et al&lt;sup&gt;94&lt;/sup&gt;</td>
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<tr>
<td>HLA</td>
<td>6p21.3</td>
<td>DRB1*1501</td>
<td>HLA haplotypes were reported to be associated with an earlier age at disease onset, sex dimorphism, and severe, relapsing-remitting, and mild MS courses</td>
<td>Engell et al&lt;sup&gt;95&lt;/sup&gt;, Madigand et al&lt;sup&gt;96&lt;/sup&gt;, Duquette et al&lt;sup&gt;97&lt;/sup&gt;, de la Concha et al&lt;sup&gt;98&lt;/sup&gt;, Celius et al&lt;sup&gt;99&lt;/sup&gt;, Masterman et al&lt;sup&gt;100&lt;/sup&gt;, Hensiek et al&lt;sup&gt;101&lt;/sup&gt;</td>
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<td>HLA haplotypes were reported to have no influence on disease course</td>
<td>Poser et al&lt;sup&gt;102&lt;/sup&gt;, Runmarker et al&lt;sup&gt;103&lt;/sup&gt;, Weishenker et al&lt;sup&gt;104&lt;/sup&gt;, McDonnell et al&lt;sup&gt;105&lt;/sup&gt;, Barcellos et al&lt;sup&gt;106&lt;/sup&gt;, Villoslada et al&lt;sup&gt;107&lt;/sup&gt;, Kira et al&lt;sup&gt;108&lt;/sup&gt;</td>
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<td>No DRB1 association in some Asian populations who have a restricted disease, termed neuromyelitis optica, in which optic nerve and/or spinal cord involvement predominates</td>
<td>Hauser et al&lt;sup&gt;109&lt;/sup&gt;</td>
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<td>A high prevalence of DR2 was observed in patients with acute unilateral optic neuritis; its presence was associated with increased odds for developing definite MS; the association was most apparent among patients with signal abnormalities on the baseline brain MRI</td>
<td>Olerup et al&lt;sup&gt;110&lt;/sup&gt;, de la Concha et al&lt;sup&gt;111&lt;/sup&gt;, McDonnell et al&lt;sup&gt;112&lt;/sup&gt;, Weishenker et al&lt;sup&gt;113&lt;/sup&gt;, Kantarci et al&lt;sup&gt;114&lt;/sup&gt;</td>
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<td>A number of small studies failed to show any association between PPMS and DR2, although a larger study from Northern Ireland appeared to show the association; others suggested an association between PPMS and the HLA-DRβ4 haplotype, although a post hoc analysis is consistent with an effect decreasing the risk of relapsing-remitting MS in HLA-DRβ4+ individuals rather than increasing the risk of PPMS</td>
<td>Barcellos et al&lt;sup&gt;115&lt;/sup&gt;, Shalev et al&lt;sup&gt;116&lt;/sup&gt;</td>
</tr>
<tr>
<td>CD24</td>
<td>6p21</td>
<td>ORF A→V</td>
<td>50% of CD24 V/V patients with an expanded disability status scale score of 6.0 reached the milestone in 5 y, whereas the CD24 A/V and CD24 A/A patients did so in 16 y and 13 y, respectively</td>
<td>Zhou et al&lt;sup&gt;117&lt;/sup&gt;</td>
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</table>

(continued)
Table. Examples of Gene Variants That Have Been Associated With Multiple Sclerosis Phenotype (cont)

<table>
<thead>
<tr>
<th>Gene or Locus</th>
<th>Chromosomal Location</th>
<th>Allele</th>
<th>Associate Phenotype</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESR1</td>
<td>6q21.5</td>
<td>PvuII and XbaI RFLP</td>
<td>The P allele–positive patients had a significantly higher progression of disability and a worse-ranked MS severity score; the study also suggests an interaction between the ESR1 genotype and DR2 in women with MS</td>
<td>Kikuchi et al.117</td>
</tr>
<tr>
<td>CD59</td>
<td>10q24.1</td>
<td>−670A or exon 7 74C</td>
<td>Sex dimorphism</td>
<td>Kantarci et al.119</td>
</tr>
<tr>
<td>CNTF</td>
<td>11q12</td>
<td>Exon 2/–6, G→A null mutation</td>
<td>Patients with the CNTF −/− genotype had significantly earlier onset (17 y vs 27 y) with predominant motor symptoms</td>
<td>Giess et al.120</td>
</tr>
<tr>
<td>CRYAB</td>
<td>11q22.3–23.1</td>
<td>−650C</td>
<td>Noninflammatory, neurodegenerative phenotype characterized by rapid PPMS course</td>
<td>van Veen et al.121</td>
</tr>
<tr>
<td>MEFV</td>
<td>16p13.3</td>
<td>694M→W</td>
<td>Rapid progression to disability in non–Ashkenazi Jewish patients</td>
<td>Shinar et al.122</td>
</tr>
<tr>
<td>APOE</td>
<td>19q13.2</td>
<td>APOE4</td>
<td>Increased severity, rate of progression, or disease brain activity</td>
<td>Evangelou et al.123 Fazekas et al.124 Hogh et al.125 Chapman et al.126 Fazekas et al.127 Enzinger et al.128</td>
</tr>
<tr>
<td></td>
<td></td>
<td>APOE2</td>
<td>No effect</td>
<td>Ferri et al.129 Weatherby et al.130 Masterman et al.131 Schreiber et al.132 Savetzieri et al.133</td>
</tr>
<tr>
<td>TGFβ1</td>
<td>19q13</td>
<td>−509/C and codon 10/1186T</td>
<td>Decreased severity and progression to chronic progressive disease</td>
<td>Ballerini et al.134 Schmidt et al.135 Kantarci et al.136</td>
</tr>
</tbody>
</table>

Abbreviations: A/V, alanine/valine; EDSS, Expanded Disability Status Scale; M, methionine; MRI, magnetic resonance imaging; MS, multiple sclerosis; PPMS, primary progressive multiple sclerosis; RFLP, restriction fragment length polymorphism; Rs, reference SNP; SNP, single nucleotide polymorphism; VNTR, variable number of tandem repeats; V/V, valine/valine.

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REFERENCES

19. Allegretta M, Nicklas JA, Sriram S, Albertini RJ. T cells responsive to myelin


17. Tsuchida T, Parker KC, Turner RV, McFarland HF, Coligan JE, Biddison WE.


11. Rep MH, van Oosten BW, Roos MT, Ader HJ, Polman CH, van Lier RA. Treat-

14. Killestein J, Kalkers NF, Meilof JF, Barkhof F, van Lier RAW, Polman CH. TNFa

8. Lovett-Racke AE, Trotter JL, Lauber J, Perrin PJ, June CH, Racke MK. De-

9. Scholz C, Patton KT, Anderson DE, Freeman GJ, Hafler DA. Expansion of au-

7. Shirai A, Asaki Y. Development of autoimmune in MRL/lpr/lpr mice. 

27. Shirai A, Aoki I, Danni M, Mond JJ, Kliman DM. Treatment with dextran-


25. Chen VS, Bucala R, Shank D, et al. Th1 and Th2 cytokines induce expression of


