Effect of Rituximab on the Peripheral Blood and Cerebrospinal Fluid B Cells in Patients With Primary Progressive Multiple Sclerosis

Nancy L. Monson, PhD; Petra D. Cravens, PhD; Elliot M. Frohman, MD, PhD; Kathleen Hawker, MD; Michael K. Racke, MD

Background: Rituximab, an anti-CD20 monoclonal antibody that depletes CD20+ B cells, has demonstrated efficacy in peripheral neurological diseases. Whether this efficacy can be translated to neurological diseases of the central nervous system with possible autoimmune B-cell involvement remains unknown.

Objective: To determine the effect of rituximab on cerebrospinal fluid B cells in patients with multiple sclerosis.

Design: Four patients with primary progressive multiple sclerosis were treated with rituximab. Cerebrospinal fluid and peripheral blood B-cell subsets were identified by flow cytometry from each patient before and after rituximab treatment.

Results: The B cells in cerebrospinal fluid were not as effectively depleted as their peripheral blood counterparts. Rituximab treatment temporarily suppressed the activation state of B cells in cerebrospinal fluid. The residual B cells underwent expansion after rituximab treatment.

Conclusion: The effect(s) of rituximab on the cerebrospinal fluid B-cell compartment is limited in comparison with the effect(s) on the B cells in the periphery, but this finding will need to be confirmed in a larger group of MS patients.

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Multiple sclerosis (MS) is an inflammatory, demyelinating disease of the central nervous system (CNS) that likely involves an autoimmune response directed against myelin-associated antigens. Evidence exists that possibly implicates B cells in the development and perpetuation of MS.1-11 Thus, efforts to address whether B-cell-depleting therapies may have a place in therapeutic regimens for patients with MS (hereafter referred to as MS patients) have begun.

Rituximab (Genentech, Inc, San Francisco, Calif; IDEC Pharmaceuticals Corp, San Diego, Calif) is a chimeric murine/human IgG1κ monoclonal antibody. It targets CD20, a transmembrane phosphoprotein expressed on most B cells, except for plasma B cells.12-14 Rituximab depletes B cells by binding to the CD20 molecule and thereby initiating complement-dependent cytolysis or antibody-dependent cell-mediated cytotoxicity. Rituximab has clear clinical benefit for patients with neoplastic B-cell-mediated diseases15 and treatment of anti-GM1 polyneuropathy.16 Whether this efficacy of rituximab in peripheral neurological diseases with autoimmune B-cell involvement can be translated to neurological diseases of the CNS with possible autoimmune B-cell involvement remains unknown.

The objective of this study was to determine the effect of rituximab on B cells in the peripheral blood (PB) and cerebrospinal fluid (CSF) of MS patients.

METHODS

STUDY POPULATION

Five patients were recruited for rituximab therapy at the University of Texas Southwestern Medical Center at Dallas on the basis of previous response to plasmapheresis and continued disease progression. All patients signed a consent form approved by the institutional review board. Their clinical presentation is summarized in Table 1.

THERAPY

All 5 patients were treated with a weekly dose of intravenous rituximab (375 mg/m^2) for 4 consecutive weeks.

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B-CELL FREQUENCY ASSESSMENT

Four of the 5 patients consented to donate a PB sample before and after completion of rituximab therapy. Approximately 10 mL of heparinized PB was collected at each sampling. Mononuclear cells from the PB were isolated by Ficoll-Hypaque sedimentation as described. Two of these patients also consented to donate CSF at the same time points as the blood samplings. The CSF cells were isolated by centrifugation of the CSF. The PB and CSF cells were stained with a phycoerythrin-labeled anti-CD19 monoclonal antibody and other markers that identify B-cell subsets (Table 2). The cells were collected using a flow cytometer (FACStar Plus; Becton Dickinson, San Jose, Calif) and the CD19+ B-cell frequencies and light-scatter characteristics analyzed using CellQuest software (Becton Dickinson). We used the $\chi^2$ test to compare the frequencies of CD19+ B cells (before and after rituximab treatment) in the PB and CSF.

RESULTS

EFFECT OF RITUXIMAB ON PERIPHERAL B-CELL FREQUENCY

Four of the 5 patients consented to donate a PB sample before and after completion of rituximab therapy. Approximately 10 mL of heparinized PB was collected at each sampling. Mononuclear cells from the PB were isolated by Ficoll-Hypaque sedimentation as described. Two of these patients also consented to donate CSF at the same time points as the blood samplings. The CSF cells were isolated by centrifugation of the CSF. The PB and CSF cells were stained with a phycoerythrin-labeled anti-CD19 monoclonal antibody and other markers that identify B-cell subsets (Table 2). The cells were collected using a flow cytometer (FACStar Plus; Becton Dickinson, San Jose, Calif) and the CD19+ B-cell frequencies and light-scatter characteristics analyzed using CellQuest software (Becton Dickinson). We used the $\chi^2$ test to compare the frequencies of CD19+ B cells (before and after rituximab treatment) in the PB and CSF.

Table 1. Patient Summary

<table>
<thead>
<tr>
<th>Patient No./Sex/Age, y</th>
<th>Type of MS</th>
<th>Time Since Initial Symptoms, y</th>
<th>Time Since Diagnosis, y</th>
<th>EDSS Before Rituximab</th>
<th>MRI Findings</th>
<th>OCB</th>
<th>IgG Synthesis, mg/dL*</th>
</tr>
</thead>
<tbody>
<tr>
<td>M116/F/61†</td>
<td>PP</td>
<td>23</td>
<td>20</td>
<td>7</td>
<td>Periventricular T2 lesions</td>
<td>Negative</td>
<td>8.36</td>
</tr>
<tr>
<td>M154/F/59</td>
<td>PP</td>
<td>26</td>
<td>22</td>
<td>6</td>
<td>Periventricular T2 lesions</td>
<td>Positive</td>
<td>0.85</td>
</tr>
<tr>
<td>M188/F/54</td>
<td>PP</td>
<td>5</td>
<td>3</td>
<td>8</td>
<td>Periventricular T2 lesions</td>
<td>Negative</td>
<td>0.00</td>
</tr>
<tr>
<td>M191/F/52</td>
<td>OND</td>
<td>2</td>
<td>1</td>
<td>NP</td>
<td>Normal</td>
<td>Negative</td>
<td>NP</td>
</tr>
<tr>
<td>M602/M/44</td>
<td>PP</td>
<td>24</td>
<td>17</td>
<td>7</td>
<td>Cervical atrophy</td>
<td>NP</td>
<td>NP</td>
</tr>
</tbody>
</table>

Abbreviations: EDSS, Expanded Disability Status Scale; MRI, magnetic resonance imaging; MS, multiple sclerosis; NP, not performed; OCB, oligoclonal banding; OND, other neurological disease; PP, primary progressive.

*The reference range for IgG synthesis is 0-12.
†This patient also had elevated anti-GM1 and antisulfatide antibody levels and a coexistent peripheral neuropathy.

Table 2. Marker Expression on B-Cell Subsets

<table>
<thead>
<tr>
<th>B Cells</th>
<th>CD19/20</th>
<th>FSC/SSC</th>
<th>CD38</th>
<th>IgM</th>
<th>IgD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immature</td>
<td>Bright</td>
<td>Low</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Naive</td>
<td>Bright</td>
<td>Low</td>
<td>–</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>Recently activated</td>
<td>Bright</td>
<td>Low</td>
<td>–</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>Advanced memory*</td>
<td>Dim</td>
<td>High</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Plasma B cells</td>
<td>Dim/−</td>
<td>High</td>
<td>+</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Abbreviations: FSC/SSC, forward scatter vs side scatter; minus sign, no expression; plus sign, expression.

*Includes postswitch memory and preplasma B cells.

Table 3. CD19+ Frequencies in the PBL Samples of Patients With MS Receiving Rituximab

<table>
<thead>
<tr>
<th>Patient Code, Time of Sampling by Rituximab Treatment</th>
<th>CD19+ in PBL, %</th>
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</thead>
<tbody>
<tr>
<td>M116 Before</td>
<td>18.43†</td>
</tr>
<tr>
<td>1 mo after</td>
<td>0.14†</td>
</tr>
<tr>
<td>18 mo after†</td>
<td>4.42†</td>
</tr>
<tr>
<td>20 mo after†</td>
<td>7.91†</td>
</tr>
<tr>
<td>M154 Before</td>
<td>3.80†</td>
</tr>
<tr>
<td>2 mo after</td>
<td>0.02†</td>
</tr>
<tr>
<td>14 mo after†</td>
<td>7.42†</td>
</tr>
<tr>
<td>M191† Before</td>
<td>6.3</td>
</tr>
<tr>
<td>14 mo after†</td>
<td>1.58†</td>
</tr>
<tr>
<td>M602 Before</td>
<td>6.5</td>
</tr>
<tr>
<td>2 mo after†</td>
<td>0.32†</td>
</tr>
</tbody>
</table>

Abbreviations: MS, multiple sclerosis; PBL, peripheral blood leukocytes.

*Patient M116 was retreated with rituximab immediately after this sampling.
†Statistically different from the pretreatment CD19+ frequency in the PBL, according to $\chi^2$ analysis.

The PB and CSF samples were collected from MS patients M116 and M154 before and after rituximab treatment. Only PB was sampled from MS patient M602 and a single patient with progressive myelopathy (patient M191). The samples were stained for CD19, a B-cell marker whose expression parallels that of CD20. The CD19+ B cells were effectively depleted in the periphery after rituximab therapy in all 4 patients (Table 3), as expected. Patient M116 had 18.43% CD19+ PB B cells before rituximab therapy, which decreased to 0.14% 1 month after rituximab therapy (Table 3). The other 3 patients demonstrated similar significant decreases in CD19+ PB B-cell frequencies after rituximab therapy. Patient M116 had a second course of rituximab, and 2 months after this second course, the CD19+ B-cell population was not depleted (4.42% vs 7.91%). This resistance to depletion on retreatment with rituximab has been reported previously.

The time frame in which CD19+ PB B-cell frequencies recovered varied between the patients (Table 3). The CD19+ B-cell frequency in patient M116 had increased to 4.42% 18 months after rituximab treatment, but did not fully recover to the pretreatment B-cell frequency of 18.43%. Patient M191 also did not recover to the pretreatment B-cell frequency at 14 months after rituximab treatment. In contrast, patient M154 had a larger post-treatment frequency than that observed before rituximab treatment. Thus, there will likely be individual variability in the time frame and extent of CD19+ PB B-cell frequency recovery after rituximab therapy.
The CD19dim CSF B cells were CD19bright CD38+IgM+IgD− (see oval gate in Figure 1C). Thus, the residual B cells were postswitch B cells that had not yet differentiated to a plasma B-cell phenotype. There was also a population of cells that were CD19bright CD38−IgM−IgD+ (see red gate in Figure 1C), which are likely immature B cells (Table 1) that have recently emerged from the bone marrow to begin repopulating the peripheral B-cell pool.

Approximately 80% of the CD19dim CSF B cells were IgM−IgD−CD38+ (Figure 1E and rectangular gate in Figure 1F), which stratified them as plasma B cells. The other approximately 20% of the CD19dim B cells were IgM+IgD−CD38+, and had thus not differentiated to a plasma B-cell phenotype. The CD19+CD38+ population would include plasma B cells as well, but this population also contains T cells, so an accurate analysis of the plasma B cells in this population could not be ascertained.

**ACTIVATION STATUS OF PERIPHERAL B CELLS IN RESPONSE TO RITUXIMAB**

Activated B cells (such as plasma B cells) are generally larger and more granular than their naive counterparts. This phenomenon can be observed by flow cytometric light-scatter characteristics, looking at the placement of B cells in the forward scatter vs side scatter (FSC/SSC) plot, which separates cells by size and granularity, respectively. To identify B-cell subpopulations after rituximab therapy, we reanalyzed the B-cell compartments in the CSF and PB from the time point before and 2 time points after rituximab therapy in patients M116 and M154.

There were 2 populations of CD19+ PB B cells (bright and dim) in patient M116 (Figure 1A), so we analyzed them separately for their light-scatter profiles. Most of the B cells in the PB of patient M116 before rituximab therapy were CD19bright (78.8%) (Figure 1A), and were mostly contained in the typical lymphocyte region (ie, low FSC/SSC) (red dots) (Figure 2A). The CD19dim B cells (green dots) (Figure 2A) were also mostly contained in the typical lymphocyte gate (ie, low FSC/SSC). This indicated that the CD19bright and CD19dim B cells were largely in a resting state.

One month after rituximab therapy, the CD19bright B cells (red dots) were largely depleted (Figure 2B), as expected. However, the CD19dim B cells (green dots) remained and maintained their resting state (low FSC/SSC). Eighteen months later, the CD19bright B cells (red dots) had repopulated the B-cell pool (Figure 2C) and were in a resting state, as had been observed before rituximab therapy. Interestingly, 18 months after rituximab therapy, the CD19dim B-cell population (green dots) had not only expanded (3.9% of CD19+ B cells before vs 96.4% of CD19− B cells after rituximab treatment), but had increased their FSC (ie, were larger in size) to a position above the lymphocyte region (Figure 2C). This light-scatter profile is consistent with a more activated state of the CD19dim B cells than that observed before rituximab therapy.

The peripheral B cells from patient M154 behaved in a similar manner (Figure 3), with the CD19bright B cells (red dots) located in the typical lymphocyte region before rituximab treatment (Figure 3B), followed by depletion of the CD19bright B cells 2 months after rituximab therapy (Figure 3C), and finally, repopulation of the typi-
cal lymphocyte region 14 months after rituximab therapy with CD19<sup>bright</sup> B cells (Figure 3D). The CD19<sup>dim</sup> B cells (green dots) were also present before rituximab therapy (Figure 3B), but remained largely in the typical lymphocyte region (low FSC/SSC), and remained so 2 months after rituximab treatment (Figure 3C). Fourteen months later, the CD19<sup>dim</sup> B-cell population had expanded (20.1% of CD19<sup>+</sup> B cells before vs 91.9% of CD19<sup>+</sup> B cells after rituximab therapy) and were in a more activated state.

### ACTIVATION STATUS OF CSF B CELLS IN RESPONSE TO RITUXIMAB

We have observed that most of the CSF B cells are not located within the typical lymphocyte region, but instead have increased light-scatter profiles to reflect a more activated phenotype. The CSF B cells from patient M116 are a typical example of that, having few CD19<sup>bright</sup> B cells (red dots) relative to PB (compare Figure 2A and Figure 2D), and most CD19<sup>dim</sup> B cells (green dots) were located above the resting lymphocyte region (Figure 2D) before rituximab treatment. One month after rituximab therapy, most of the CSF B cells were CD19<sup>dim</sup> (green dots), and had relocated to the resting lymphocyte region (Figure 2E). Twenty months after rituximab therapy, some CD19<sup>bright</sup> CSF B cells (red dots) were observed within the typical lymphocyte region. However, the CD19<sup>dim</sup> B cells (green dots) had increased light-scatter profiles, indicating a heightened state of activation (Figure 2F) similar to their light-scatter profile before rituximab therapy. In addition, the CD19<sup>dim</sup> B cells (green dots) had expanded in comparison with the population before rituximab treatment (55% of CD19<sup>+</sup> B cells before vs 77% CD19<sup>+</sup> B cells after rituximab therapy).

Most of the CSF B cells from patient M154 before rituximab therapy were CD19<sup>dim</sup> (77.8%), and had a high light-scatter profile (Figure 3F). We had observed the same profile of CSF B cells from patient M116, and consider this pattern typical for CSF B cells, which are more activated than their peripheral counterparts. Two months after rituximab therapy, some CD19<sup>bright</sup> CSF B cells (red dots) were still detectable (Figure 3G), but the CD19<sup>dim</sup> B cells (green dots) remained and, interestingly, displayed a low light-scatter profile, indicative of a resting state (Figure 3G). However, 14 months after rituximab therapy, some CD19<sup>bright</sup> CSF B cells (red dots) had repopulated. The CD19<sup>dim</sup> B cells (green dots) had expanded significantly (20.2% of CD19<sup>+</sup> B cells before vs 94.4% of CD19<sup>+</sup> B cells after rituximab therapy) and had assumed their activated state (high light-scatter profile) (compare Figure 3H and Figure 3F).

### COMMENT

It is evident that CD19<sup>+</sup> B cells were depleted in the periphery within 1 to 2 months after rituximab therapy in the PB of all 3 patients. Even patient M191 maintained a...
depleted CD19+ B-cell population in the periphery 14 months after rituximab therapy. However, the PB CD19+ B-cell population was partially or fully reconstituted between 14 and 18 months after rituximab therapy, indicating that the inhibitory effect of rituximab on B cells no longer exists.

The effect of rituximab on the B-cell pool within the CNS tissue is not as well-defined, but it becomes an issue when considering rituximab as a therapeutic agent in B-cell–mediated diseases of the CNS. We have examined the effect of rituximab on CD19+ CSF B cells in 2 MS patients, which likely represents a subset of B cells...
that populate the CNS tissue. The CD19<sup>+</sup> CSF B cells showed a mild decrease 1 month after rituximab therapy, followed by a significant expansion 18 and 20 months after rituximab therapy that were 5- to 9-fold the CD19<sup>+</sup> B-cell frequency before rituximab therapy. However, the CD19<sup>+</sup> CSF B cells in patient M154 were not affected by rituximab. This was in direct contrast to what had been routinely observed in PB B cells in response to rituximab, and prompts the question of whether this lack of CSF B-cell depletion has any repercussions on the potential efficacy of rituximab treatment of MS.

There are at least 2 possible scenarios that could account for the lack of CSF B-cell depletion. First, the concentration of rituximab that reaches the CSF can be nearly 10-fold less than the concentration readily achieved in the PB. Thus, if therapeutic levels of rituximab cannot reach the CSF, depletion of CSF B cells should not be expected. However, the observation that only 10% or less of the rituximab concentration that is reached in the PB is obtainable in the CSF is based on patients whose blood-brain barrier is not compromised, as it is in most MS patients. Thus, perhaps higher CSF rituximab concentrations can be achieved in MS patients whose blood-brain barrier has been compromised. This concept has not been rigorously tested. Second, rituximab is more effective at depleting B cells that have high expression of CD20, such as naïve B cells. However, most CSF B cells are advanced memory or plasma B cells, which express CD19/20 dimly, rendering them resistant to rituximab.

Rituximab also appears to affect CD19<sup>dim</sup> B-cell activation states, because the initial activated phenotype of the CD19<sup>dim</sup> CSF B cells was suppressed after rituximab therapy. However, these CD19<sup>dim</sup> CSF B cells had reestablished their activation phenotype 14 and 20 months after rituximab therapy. It is unclear how the suppression of this activation state shortly after treatment occurs. It is possible that rituximab itself asserts some form of suppression on residual B cells, or that some other changes in the CSF environment in response to rituximab causes CD19<sup>dim</sup> B cells to enter a resting state. What effect this resting state of the residual CD19<sup>dim</sup> CSF B cells has on disease status remains unknown, although it is compelling to predict that this suppression of the residual B cells by rituximab (directly or indirectly) will translate to a clinical improvement for the patients. However, it is clear that at some point (presumably when rituximab levels drop below a certain concentration), the surviving CSF B cells resume their activated phenotype.

This activation suppression phenomenon we observed with the CSF CD19<sup>dim</sup> B cells was not observed in the peripheral CD19<sup>dim</sup> B-cell population because these cells are typically resting. However, the CD19<sup>dim</sup> B cells that survived in the periphery had acquired an activated state after rituximab therapy. Whether this activation state of CD19<sup>dim</sup> peripheral B cells parallels that of the CD19<sup>dim</sup> CSF B cells will need to be investigated, as well as what effect this might have on the reconstituted B-cell pool.

We also observed an expansion of PB and CSF CD19<sup>dim</sup> B cells after rituximab therapy. Expansion of residual CD19<sup>dim</sup> B cells may be based on the theory of space threshold, which suggests that there is a finite amount of space where cells are allowed to populate, and once the CD19<sup>bright</sup> B cells were depleted, the CD19<sup>dim</sup> B cells took advantage of the extra space and expanded as observed in these 2 patients. Alternatively, the chemokine milieu may have shifted during rituximab therapy, resulting in an influx of CD19<sup>dim</sup> B cells from other compartments (such as the bone marrow), and subsequent expansion. Third, perhaps residual CD19<sup>bright</sup> B cells that survived rituximab treatment were able to rapidly become activated and differentiate. However, for this hypothesis to apply to the CSF B cells, the concept that B cells can differentiate and become activated outside the context of germinal centers must be substantiated.

We have observed typical depletion of PB B cells after rituximab therapy in patients with primary progressive MS. Rituximab does not deplete CSF B cells efficiently because most CSF B cells are highly activated advanced memory or plasma B cells that express little or no CD20. Recovery of the initial B-cell frequencies will likely vary among individuals. Alterations in activation and expansion status of PB and CSF B cells in response to rituximab requires further study to resolve the mechanism(s) underlying these phenomena.

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REFERENCES


