Anti-CD20 (Rituximab) therapy for anti-interferon-gamma autoantibody-associated nontuberculous mycobacterial infection

Rituximab for IFN-γ autoantibody associated NTM

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Abstract

Patients with anti-IFN-γ autoantibodies have impaired IFN-γ signaling leading to severe disseminated infections with intracellular pathogens, especially nontuberculous mycobacteria. Disease may be severe and progressive, despite aggressive treatment. To address the underlying pathogenic IFN-γ autoantibodies we used the therapeutic monoclonal rituximab (anti-CD20), to target patient B cells. All subjects received between 8 and 12 doses of rituximab within the first year to maintain disease remission. Subsequent doses were given for relapsed infection. We report four patients with refractory disease treated with rituximab who had clinical and laboratory evidence of therapeutic response as determined by clearance of infection, resolution of inflammation, reduction of anti-IFN-γ autoantibody levels, and improved IFN-γ signaling.
Introduction

The interferon-gamma (IFN-γ)-interleukin-12 (IL-12) axis is critical for control of mycobacteria as well as other opportunistic pathogens\(^1\). High titer neutralizing anti-IFN-γ autoantibodies affect the same pathway and cause a syndrome of disseminated nontuberculous mycobacterial and other opportunistic infections\(^2\)-\(^5\). These patients can have severe and progressive disease despite prolonged antimicrobial therapy, which can result in drug toxicity and therapeutic failure.

Rituximab is a chimeric monoclonal antibody directed against human CD20 on mature B cells and plasmablasts that causes rapid and sustained depletion of circulating and tissue-based B cells\(^6\). Diseases for which Rituximab is FDA approved include B cell lymphoma, dosed at 375mg/m\(^2\) for 4 or 8 doses\(^6\),\(^7\) or rheumatoid arthritis, dosed at 1000mg for 2 doses on day 1 and day 15\(^8\). Rituximab has also been used off-label for the treatment of diseases caused by pathogenic autoantibodies including the anti-desmoglein 3 autoantibodies of pemphigus vulgaris\(^9\), the anti-acetylcholine or anti-muscle specific kinase autoantibodies of myasthenia gravis\(^10\),\(^11\), the anti-granulocyte-macrophage-colony stimulating factor [GM-CSF] autoantibodies of pulmonary alveolar proteinosis\(^12\), and the anti-erythropoietin autoantibodies of pure red cell aplasia\(^13\).

We used rituximab in four patients with high-titer anti-IFN-γ autoantibodies who had progressive refractory nontuberculous mycobacterial disease despite aggressive anti-infective treatment. Our initial approach was to treat according to a lymphoma regimen, given our aim of depleting B cells. Additional doses of rituximab were given for signs and symptoms consistent with infection persistence or relapse.
Materials and Methods

Subjects
The four patients were seen at the National Institutes of Health and consented to evaluation and treatment of disseminated nontuberculous mycobacterial infection under protocol 01-I-0202. Control plasma and peripheral blood mononuclear cells (PBMC) were obtained though the National Institutes of Health Blood Bank under appropriate protocols.

Clinical monitoring
Patients had routine laboratories including HIV testing, complete blood count with differential, serum electrolytes, renal and hepatic function chemistries, inflammatory markers, quantitative immunoglobulin levels and lymphocyte markers including total T cells (CD3+; BD Pharmigen); CD4+ T cells (Immunotech); CD8+ T cells (Immunotech); CD20+ B cells (BD Pharmigen); and CD 16+ or CD 56+ NK cells (BD Pharmigen). Disease activity was determined by evidence of active infection on CT scan, bone scan, culture, or smear, as indicated. Treatment and clinical data were collected via review of electronic chart records. Salient clinical features of disease activity were compiled retrospectively into a scoring system.

Plasma collection
Plasma from each subject was collected and stored at -80°C before, during (2-9 months after start) and after treatment (1-4 years after start) with rituximab. All samples were tested at first thaw. For each patient, the same three plasma collection dates for pre, during, and post rituximab treatment were used across experiments. For patient 2,
plasma and clinical data had been collected and was studied at a time of relapse followed by retreatment.

**Determination of IFN-γ autoantibody titers**

Relative titers of IFN-γ autoantibody were determined by performing serial 10-fold dilutions of plasma and measuring IFN-γ autoantibody levels by a particle-based technique as previously described. Briefly, magnetic beads (Bio-Rad, Hercules, CA) conjugated to recombinant human IFN-γ (R&D Systems, Minneapolis, MN) were incubated 1 hour with subject or control plasma, washed, and incubated with mouse anti-human IgG conjugated to phycoerythrin (eBioscience). The beads were run on the Bio-plex (Bio-Rad) instrument and the fluorescence intensity was plotted at each dilution to generate titration curves for each patient (Graphpad Prism, version 5.0c). For all patients, a dilution factor of 1:5000 yielded a fluorescence intensity within the dynamic range of the assay and was chosen as a standard dilution factor to test antibody levels. First-thaw aliquots of plasma for each patient from each date were tested at least 3 times at 1:5000 dilution, with error bars indicating the range of results obtained.

**Cell culture and stimulation**

PBMC were obtained by density gradient centrifugation as previously described, and cultured at $10^6$ cells/mL in complete medium consisting of RPMI 1640 (Gibco BRL), 2mM glutamine, 20mM Hepes, 0.01mg/mL penicillin/streptomycin with 10% plasma from patients or from healthy blood bank donors.

**Detection of phosphoSTAT-1 by flow cytometry**

For detection of phosphorylated signal transducer and activator of transcription (pSTAT-1), PBMC (5 x $10^5$ cells) from healthy donors were cultured in complete RPMI media
containing control or patient plasma (10%) and left unstimulated or stimulated with IFN-γ (1,000U/mL) (Intermune, Inc) or IFN-α 2b (1,000U/mL) (Merck) for 15 minutes at 37°C. Monocytes were identified by CD14 (BD pharmigen) before being fixed and permeabilized for intracellular staining with phosphoSTAT-1 (Y701) antibody (BD pharmigen) as previously described. Data were collected using FACS Calibur (BD Biosciences) and analyzed using FlowJo (Treestar).

Detection of phosphoSTAT-1 by immunoblot
For immunoblot analysis, PBMC (3x10⁶ cells/well) were cultured in RPMI medium in the presence of 10% normal or patient plasma, and left unstimulated or stimulated with IFN-α or IFN-γ (1,000U/ml) for 30 min. Cell lysates were collected and analyzed for pSTAT-1 production as described previously.

Quantitative Real Time-Polymerase Chain Reaction (qRT-PCR)
For evaluation of gene expression, PBMCs isolated from healthy donors were cultured in complete RPMI-1640 medium containing 10% normal or patient plasma at 37°C and were unstimulated or treated with IFN-γ at specified concentrations or IFN-α (1,000U/mL) for 3 hours, at which time cells were harvested for RNA isolation. Total RNA was extracted using the RNeasy kit according to the manufacturer’s protocols (Qiagen, Valencia, CA). RNA (1µg) was used for reverse transcription by oligo-dT primer (Invitrogen) and the resulting cDNA amplified by PCR using the ABI 7500 Sequence detector (Applied Biosystems, Foster City, CA). Amplification was performed using Taqman expression assays (Applied Biosystems). GAPDH was used as a normalization control and results are expressed as fold-induction over unstimulated. Since normal PBMC across individual donors can demonstrate large differences in IFN-γ responsiveness, a difference in fold-induction of IFN-γ induced RNA might reflect
differences between normals, and not the actual inhibitory capacity of the plasma. To avoid this confounder, the IFN-γ-induced RNA fold-induction for normal PBMC with normal plasma was set at 100% and the IFN-γ-induced RNA fold-induction for the same PBMC with patient plasma was calculated as a percentage of normal.

Results

Patients
All subjects were HIV negative, had proven anti-IFN-γ autoantibodies as described previously, and although modest abnormalities were noted, none had quantitative deficiencies in lymphocyte subsets sufficient to explain their infections (Table 1). Patient 2 was noted to have a mildly decreased CD4 count (291/µl) immediately prior to treatment, but CD4 counts obtained previously, during ongoing infection, were normal at 471/µl and 530/µl.

Disseminated nontuberculous mycobacterial infection was shown by culture from multiple noncontiguous sterile sites of *M. abscessus, M avium* and *M intracellulare* as listed in Table 2. All subjects had demonstrated progressive mycobacterial infection over 1-5 years in the context of treatments with 3 or more antimycobacterial agents before rituximab treatment (Table 2).

Rituximab was given at 375mg/m² weekly for at least 4 doses and then at wider intervals (Figure 1). All patients received between 8 and 12 doses over the first year with subsequent additional doses determined by recurrence of infection. All patients had transient complete elimination of CD19+ B cells in the peripheral blood following rituximab. B cells recovered to the normal range in all patients at approximately 1 year.
after rituximab, with B cell levels often detectable before that, similar to previous reports\textsuperscript{17} (figure 1, table 2). All patients had improvement in inflammatory markers such as hypergammaglobulinemia with total IgG decreasing to normal, as well (Figure 1).

All patients had objective evidence of progressive improvement initially and remission or cure of infection after rituximab, as determined by clearance of cultures from previously infected sites, radiographic improvement of sites of soft tissue and bone infections, and weight gain (Table 2). These were the features that prompted initial use and subsequent retreatment with rituximab. Using these clinical indicators of systemic infection we developed a scoring system retrospectively, to quantify the degree of disease activity (Table 3).

\textit{Anti-IFN-\textgamma{} autoantibody titers}

Anti-IFN-\textgamma{} autoantibodies were measured by a particle-based technology\textsuperscript{14}. Titration curves using serial dilutions of subject plasma generated sigmoidal curves at each time point to determine a dilution factor within the dynamic range of the assay (Figure 2A). Relative antibody titers were determined at 1:5000 dilution for each subject. Antibody titers decreased by between 1-2 logs from baseline in all subjects (Figure 2B).

\textit{Plasma-mediated inhibition of IFN-\textgamma{}-stimulated STAT-1 phosphorylation}

Plasma inhibition of IFN-\textgamma{} signaling was followed by flow cytometry (Figure 3) and corroborated by immunoblot (not shown). Stimulated normal PBMC were assayed for pSTAT-1 production in the presence of control or subject plasma following stimulation with IFN-\textalpha{} or IFN-\textgamma{}. In all patients, IFN-\textalpha{}-induced pSTAT-1 generation was preserved at all time points (shown for baseline time point, Figure 3A). In contrast, all baseline plasma samples completely inhibited IFN-\textgamma{} induced pSTAT-1 production. Following
treatment with rituximab, plasma from all subjects allowed IFN-γ-induced STAT-1 phosphorylation (Figure 3A). The degree of IFN-γ stimulation permitted by patient plasma was calculated across time points as a % of total stimulation observed by normal PBMC in the presence of normal plasma (IFN-γ-induced pSTAT-1 mean fluorescence intensity in CD14+ cells, ratio of stimulated/unstimulated)(Figure 3B).

Rituximab and IFN-γ- responsive gene expression
Plasma inhibition of IFN-γ-induced gene transcription was studied using normal PBMCs incubated with 10% patient plasma unstimulated or stimulated with IFN-γ for 3 hours prior to collecting RNA for gene expression. Baseline plasma from all patients inhibited IFN-γ-induced transcription of CXCL9, CXCL10 and CXCL11. After treatment with Rituximab, plasma from all patients showed partial reconstitution of IFN-γ-induced chemokine expression. Interestingly, plasma from patient 4 did not allow gene transcription following IFN-γ 400U/ml for any time point. Therefore, we increased the dose of IFN-γ to overcome plasma inhibition and at 3000U/ml her plasma demonstrated a progressive alleviation of IFN-γ signal inhibition after treatment with rituximab, akin to the other 3 patients (Figure 3C).

Discussion
Our patients were all previously healthy Asian women with adult-onset of disseminated nontuberculous mycobacteria and high-titer anti-IFN-γ autoantibodies, similar to previous reports\(^2, 3, 5, 18-22\). Patient 2 had a slightly decreased CD4 lymphocyte count but not low enough to cause disseminated nontuberculous mycobacterial disease. All patients had been healthy into adulthood, whereas primary immunodeficiencies tend to present early in life. All patients had extensive disease with nontuberculous mycobacteria that continued to progress over years of extensive antimycobacterial and other adjunctive
therapy including plasmapheresis (1 patient) and exogenous IFN-γ (3 patients). Within 2-6 months after initiation of rituximab treatment, all patients had marked clinical, radiologic, and laboratory improvement. All patients had improvement of inflammatory markers, although some did not completely normalize. This is not surprising given the chronic nature of this illness, potential for relapse, and ongoing need for antimicrobials. In conjunction with clinical improvement, we found convincing reduction in autoantibody titers in all 4 patients, with concordant relief of plasma-mediated inhibition of IFN-γ signaling.

Our patients received modestly differing amounts of rituximab at different dosing schedules, but all patients received between 8 and 12 doses of Rituximab in the first year. Subsequent doses were given for signs and symptoms of persistent or relapsed infection. All patients had been on long duration, best tolerated, optimized anti-infective therapy. Despite aggressive antimicrobials, all had progressive infection. Therefore, changes of antiinfectives are unlikely explanations of the striking clinical responses, decline of antibody titers, and amelioration of plasma-mediated IFN-γ signaling inhibition.

Rituximab is FDA approved for treatment of lymphoma at 375/ m² weekly for 4-8 doses and rheumatoid arthritis (RA), which is given as two, 1000mg doses at day 1 and day 15. Our patients received 375/m² (roughly 500mg) for 4 doses over a month, which is a similar dose intensity to both regimens. In contrast to patients with RA, our patients required a longer duration of therapy, between 8 and 12 doses within the first year to avoid disease progression. For example, although patient 3 had improvement over the initial 2 months of treatment, by 3 months she had recrudescence of fever, inflammatory markers and development of abscesses. In concordance with this, her titers only slightly declined (Figure 2B) and remained neutralizing (Figure 3), possibly accounting for her
persistent mycobacterial infection. Patients 2 and 4 antibody titers during treatment showed only modest initial declines with continued *in vitro* inhibitory activity, possibly due in part to the long half-life of IgG. Although patient 1 showed a greater autoantibody decline at her first time point, the collection date was 1 year after initiation of rituximab (rather than 2-8 months for the others). At the time of patient 2’s clinical relapse her plasma showed an increase in titer and *in vitro* inhibitory activity which improved after rituximab was readministered (Figure 2, Figure 3). The need for prolonged rituximab therapy in our patients, and the tendency for early relapse, may reflect persistence of autoantibody-producing cells in privileged areas, despite immediate B cell depletion in the periphery, as reported in rheumatoid arthritis23, 24.

To date none of our patients has had infectious complications due to administration of rituximab. Side effects have been minimal and limited to those previously reported, such as mild infusion reactions and two cases of transient neutropenia (1030 neutrophils/microliter for patient 2; 510 neutrophils/microliter for patient 3). None of these complications of rituximab precluded continuation of therapy. All patients demonstrated the ability to recover B cells, even after extensive treatment (table 2).

All patients demonstrated ongoing reduction of antibody titers and improved signaling over the years during and after rituximab treatment, suggesting that the benefits of CD20 depletion may accrue over time, perhaps due to depletion of plasmablasts that would replace autoantibody producing plasma cells. Interestingly, we saw a lag between clinical improvement and *in vitro* improvement of IFN-γ-signaling (Figure 3). Patient 4 had a protracted clinical course with less robust reconstitution of *in vitro* IFN-γ signaling. Nevertheless, her autoantibody titers did eventually decline concomitant with increased responsiveness to IFN-γ. *In vivo*, plasma constitutes a far greater percentage of blood
than the 10% plasma concentration we used in our experiments. While the stringency of our experimental conditions underscores the potency of these autoantibodies, it may overlook subtle alterations in antibody activity only apparent in vivo. Other factors not reflected in our measurement of antibody titer include changes in antibody avidity. The proportion of biologically active epitopes can also impact disease activity, as has been shown in pemphigus vulgaris\textsuperscript{25}. These differences in avidity and activity may account for the differences in antibody titer between subjects, indicating that titer alone is not likely to be adequate as the sole correlate of biological activity.

In severe nontuberculous mycobacterial disease, antimycobacterials alone are often ineffective without intact IFN-\(\gamma\) signaling, as evidenced by the exceedingly poor survival in patients with complete IFN-\(\gamma\) receptor deficiency\textsuperscript{1}. This in part reflects the intrinsic difficulties of treating disseminated nontuberculous mycobacterial infections, but the fact that survival is excellent in those with partial defects in IFN-\(\gamma\) signaling indicates that even small amounts of IFN-\(\gamma\) signaling are able to effectively control mycobacterial infection\textsuperscript{1}. Thus, small improvements in IFN-\(\gamma\) signal transduction during treatment with rituximab could account for improved immune function resulting in control of infection, even before this effect was detectable \textit{in vitro}. These patients had dramatic improvement in IFN-\(\gamma\) signaling from pretreatment levels that matched decreasing antibody titers and clinical improvement.

Rituximab has been effective in other diseases caused by neutralizing IgG autoantibodies, despite the fact that plasma cells do not express CD20\textsuperscript{9-13}. Possible mechanisms of action include modulation of other cell surface receptors, modulation of B cell help to T cells, and elimination of plasmablasts with slow attrition of plasma cells.
producing pathologic antibodies\textsuperscript{26, 27}. The prolonged time to clinical improvement in this disease and the protracted fall in autoantibody levels fits this hypothesis.

Not all cases of anti-IFN-\(\gamma\) autoantibody-mediated disseminated mycobacterial disease require rituximab therapy. Of the 11 patients we follow with this syndrome, so far only these four have required rituximab; the other 7 patients responded to antimycobacterial therapy alone. The cause of the difference between these two groups will be important to identify. It will be valuable to determine whether those who recover without rituximab do so because of spontaneous reduction of antibody titer or because their antibodies were less intrinsically neutralizing in the first place. However, for those patients with persistent, progressive, severe anti-IFN-\(\gamma\)-autoantibody associated infection, rituximab may be an important adjunct.

\textbf{Acknowledgements}

This work was supported by the Division of Intramural Research, National Institute of Allergy and Infectious Diseases, National Institutes of Health and from the National Cancer Institute, National Institutes of Health, under Contract No. HHSN261200800001E.

\textbf{Authorship}


Conflict-of-interest: The authors declare no competing financial interests.

Disclaimer: The content of this publication does not necessarily reflect the views or policies of the Department of Health and Human Services, nor does mention of trade
names, commercial products, or organizations imply endorsement by the U.S. Government.

References


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<tr>
<th>Parameter (absolute)</th>
<th>Patient 1</th>
<th>Patient 2</th>
<th>Patient 3</th>
<th>Patient 4</th>
<th>Normal range</th>
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<td>CD3</td>
<td>1593</td>
<td>694</td>
<td>1041</td>
<td>1285</td>
<td>650-2108</td>
</tr>
<tr>
<td>CD4/CD3</td>
<td>513</td>
<td>289</td>
<td>637</td>
<td>460</td>
<td>358-1259</td>
</tr>
<tr>
<td>CD8/CD3</td>
<td>1021</td>
<td>391</td>
<td>342</td>
<td>698</td>
<td>194-836</td>
</tr>
<tr>
<td>T4/T8 ratio</td>
<td>0.50</td>
<td>0.74</td>
<td>1.87</td>
<td>0.66</td>
<td>0.74-3.58</td>
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<tr>
<td>CD20</td>
<td>204</td>
<td>40</td>
<td>100</td>
<td>50</td>
<td>49-424</td>
</tr>
<tr>
<td>CD16+ or CD56+/CD3-</td>
<td>481</td>
<td>227</td>
<td>549</td>
<td>535</td>
<td>87-505</td>
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<tr>
<td>IFNyR-alpha on CD14</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
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Table 2. Clinical and laboratory features.

<table>
<thead>
<tr>
<th>Parameter (normal range)</th>
<th>Patient 1</th>
<th>Patient 2</th>
<th>Patient 3</th>
<th>Patient 4</th>
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<tbody>
<tr>
<td>Age/gender/ethnicity</td>
<td>46/F/Filipino*</td>
<td>69/F/Filipino'</td>
<td>50/F/Laotian</td>
<td>60/F/Vietnamese</td>
</tr>
<tr>
<td>Treatment duration prior to rituximab</td>
<td>5 years</td>
<td>7‡ years</td>
<td>&gt;1 years</td>
<td>1 year</td>
</tr>
<tr>
<td>Directed therapy prior to Rituximab‡</td>
<td>IFN-γ, Clarithromycin, Ethambutol, Isoniazid, Linezolid, Moxifloxacin, Tigecycline</td>
<td>IFN-γ, Intravenous immunoglobulin, Plasmapheresis, Amikacin, Amoxicillin/Clavulanate, Azithromycin, Ciprofloxacin, Ertapenem, Ethambutol, Isoniazid, Linezolid, Meropenem, Pyrazinamide, Rifampin, Linezolid, Tigecycline</td>
<td>IFN-γ, Clarithromycin, Ethambutol, Moxifloxacin</td>
<td>Amikacin, Azithromycin, Clarithromycin, Ethambutol, Isoniazid, Levofoxacin, Moxifloxacin, Pyrazinamide, Rifampin</td>
</tr>
<tr>
<td>Total number of Rituximab doses received</td>
<td>15 doses over 3 years</td>
<td>18 doses over 5 years</td>
<td>11 doses over 1 year</td>
<td>9 doses over 2 years</td>
</tr>
<tr>
<td>Follow-up after start of rituximab</td>
<td>5 years</td>
<td>6 years</td>
<td>4 years</td>
<td>2 years</td>
</tr>
<tr>
<td>Mycobacterial species</td>
<td><em>M. abscessus</em> Mycobacterium Avium Complex</td>
<td><em>M. abscessus</em></td>
<td><em>M. avium</em></td>
<td><em>M. intracellulare</em></td>
</tr>
<tr>
<td>Sites of infection (culture proven)</td>
<td>Lymph nodes, blood, urine, pelvic abscess, skin</td>
<td>Lymph nodes, blood, bone</td>
<td>Lymph nodes, bone, muscle</td>
<td>Bone, muscle, skin</td>
</tr>
<tr>
<td>Clinical course after Rituximab</td>
<td>Clearance of bacteremia; resolution and closure of draining lymph nodes and pelvic abscess</td>
<td>Clearance of bacteremia; resolution of vertebral osteomyelitis and cord compression; normalization of liver enzymes</td>
<td>Improved lytic and blastic bony disease; resolution of muscle abscess, resolution and closure of draining lymph nodes</td>
<td>Improved lytic and blastic bony disease; resolution of multiple draining sinuses (sternum, clavicle, scapula)</td>
</tr>
<tr>
<td>Weight gain</td>
<td>ND</td>
<td>ND</td>
<td>15 kg weight gain</td>
<td>17 kg weight gain</td>
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<tr>
<td>Culture</td>
<td>Bacteremia cleared</td>
<td>Bacteremia cleared</td>
<td>Sinus tracts closed, culture negative</td>
<td>Sinus tracts closed, culture negative</td>
</tr>
<tr>
<td>Imaging</td>
<td>Resolution of pelvic abscess</td>
<td>Healing of osteomyelitis after decompression and stabilization of spine</td>
<td>Resolution of pelvic abscesses; healing of osteomyelitis</td>
<td>Healing of osteomyelitis</td>
</tr>
<tr>
<td>Laboratory</td>
<td>B lymphocytes (normal 81-493/μl) [time to full recovery after last dose] 165 [14 months]</td>
<td>345 [12 months]</td>
<td>260 [13 months]</td>
<td>166 [7 months]</td>
</tr>
<tr>
<td><strong>rituximab</strong></td>
<td><strong>IgG (642-1730 mg/dL)</strong></td>
<td>Decreased from 2140 to 1280</td>
<td>Decreased from to 3390§ to 1160</td>
<td>Decreased from 2560 to 1050</td>
</tr>
<tr>
<td>---</td>
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<td>---</td>
<td>---</td>
</tr>
<tr>
<td><strong>Erythrocyte sedimentation rate (ESR) (&lt;42.0 mm/hr)</strong></td>
<td>Decreased from 81 to 59</td>
<td>Decreased from 64 to 34</td>
<td>Decreased from 67 to 51</td>
<td>Decreased from &gt;140 to 111</td>
</tr>
<tr>
<td><strong>C reactive protein (CRP) (&lt;0.8 mg/dL)</strong></td>
<td>Increased from 1.06 to 1.08</td>
<td>ND</td>
<td>Decreased from 0.7 to 0.5</td>
<td>Decreased from 8.8 to 4.6</td>
</tr>
<tr>
<td><strong>Anti-IFN-γ autoantibody levels</strong></td>
<td>80% decrease from baseline</td>
<td>73.7% decrease from baseline</td>
<td>65% decrease from baseline</td>
<td>58% decrease from baseline</td>
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<tr>
<td><strong>Comments</strong></td>
<td>Relapsed twice and retreated with clinical improvement</td>
<td>Relapsed twice and retreated with clinical improvement</td>
<td>Relapsed twice and retreated with clinical improvement</td>
<td>6 months of Rituximab before clinical improvement</td>
</tr>
</tbody>
</table>

* Patient #2 in prior report
f Patient #5 in prior report
‡ ≥ 3 antimycobacterials given at any time for all patients; IFN-γ treatment given prior to Rituximab and continued while receiving Rituximab for patients 2 and 3.
§ value drawn 6 months pre-treatment
Table 3. Retrospective clinical scoring before and after Rituximab administration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pt 1 pre</th>
<th>Pt 1 post</th>
<th>Pt 2 pre</th>
<th>Pt 2 post</th>
<th>Pt 3 pre</th>
<th>Pt 3 post</th>
<th>Pt 4 pre</th>
<th>Pt 4 post</th>
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<tr>
<td>Constitutional (fever, weight loss, malaise: 1 point each)</td>
<td>0 (unknown)</td>
<td>0</td>
<td>2 fever, malaise</td>
<td>0</td>
<td>2 fever, weight loss</td>
<td>0</td>
<td>2 weight loss, malaise</td>
<td>0</td>
</tr>
<tr>
<td>Clinical infection</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
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<tr>
<td>Positive blood cultures</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>Radiographic change</td>
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<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
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<tr>
<td>Hypergammaglobulinemia</td>
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<td>0</td>
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<td>0</td>
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<td>0</td>
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</tr>
<tr>
<td>Total</td>
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<td>1</td>
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<td>1</td>
<td>8</td>
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Figure Legends

Figure 1. Timeline for rituximab therapy. Each timeline represents the treatment course for one patient. Section A reflects IgG levels with normal range in gray, Section B has dots indicating months in which Rituximab was given and a number indicating how many doses at 375mg/m² were given in that month. Section C reflects total absolute B cell numbers by CD19 staining with normal range in gray. Black arrows are the times at which plasma was collected for antibody titers and functional studies for Figures 2 and 3.

Figure 2. Anti-IFN-γ autoantibody titers in relation to treatment with rituximab.
A) IFN-γ labeled beads were incubated with subject plasma at 10-fold serial dilutions to generate an antibody titration curve, as a function of fluorescence intensity, and determine a common dilution factor within the dynamic range of the assay. A representative example of the titration curve for patient 4 during rituximab therapy with the 1:5000 dilution indicated (black arrow) that lies within the linear phase of the dilution curve. B) Each patient’s antibody titer over the course of rituximab therapy was plotted at 1:5000 dilution.

Figure 3. Patient plasma inhibition of IFN-γ-induced pSTAT-1 production and RNA expression. Normal PBMC incubated in 10% control or patient plasma at time points specified in Figure 1 were left unstimulated or stimulated with IFN-α or IFN-γ for 15 minutes. CD14+ cells were assayed for intracellular pSTAT-1 by flow cytometry. A) pSTAT-1 in CD14+ cells, solid grey, unstimulated; red line, IFN-γ stimulated; blue line, IFN-α stimulated. Representative example of 1 of 3 experiments performed for each patient B) To determine the relative inhibitory effect of plasma on IFN-γ induced pSTAT-1 production, a stimulation index for each plasma (ratio of the geometric mean channel for stimulated to unstimulated) was calculated and then graphed as a percentage of the
stimulation index seen in the presence of normal plasma. Error bars represent the SEM seen for 3 separate experiments performed for each series of patient plasma. C) PBMC obtained from healthy donors (n=4 experiments per series of patient plasmas) were cultured in the presence of normal or patient plasma (10%) and stimulated with IFN-γ (400U/ml) for 3 hours. Target gene expression was evaluated by real time PCR and values are mean fold induction (± SD) relative to the unstimulated cells. GAPDH was used as normalization control. Fold-induction of IFN-γ-induced gene expression in presence of subject plasma was calculated as a percentage of the fold-induction expression seen for the same PBMCs in the presence of normal plasma. Plasma from patient 4 inhibited IFN-γ induced gene expression when stimulated with IFN-γ 400U/ml at all time points, and so the experiment was repeated using IFN-γ at a higher concentration of 3000U/ml.
Figure 1.
Figure 2.

A.

B.
Figure 3.

A. Healthy controls Pre-Treatment During Treatment Post-Treatment

Pt 1 Pt 2 Pt 3 Pt 4

RELAPSE

B. pSTAT-1 stimulation by flow cytometry

Patient 1 Patient 2 Patient 3 Patient 4

relapse

Pre-Rtx During Rtx Post-Rtx

Time-course of rituximab treatment
Figure 3.
C.

Patient 1
(IFN-γ 400U/ml)

Patient 2
(IFN-γ 400U/ml)

Patient 3
(IFN-γ 400U/ml)

Patient 4
(IFN-γ 3000U/ml)
Anti-CD20 (Rituximab) therapy for anti-interferon-gamma autoantibody-associated nontuberculous mycobacterial infection

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