

## ORIGINAL ARTICLE

# Ibrutinib in Previously Treated Waldenström's Macroglobulinemia

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## ABSTRACT

**BACKGROUND**

*MYD88*<sup>L265P</sup> and *CXCR4*<sup>WHIM</sup> mutations are highly prevalent in Waldenström's macroglobulinemia. *MYD88*<sup>L265P</sup> triggers tumor-cell growth through Bruton's tyrosine kinase, a target of ibrutinib. *CXCR4*<sup>WHIM</sup> mutations confer in vitro resistance to ibrutinib.

**METHODS**

We performed a prospective study of ibrutinib in 63 symptomatic patients with Waldenström's macroglobulinemia who had received at least one previous treatment, and we investigated the effect of *MYD88* and *CXCR4* mutations on outcomes. Ibrutinib at a daily dose of 420 mg was administered orally until disease progression or the development of unacceptable toxic effects.

**RESULTS**

After the patients received ibrutinib, median serum IgM levels decreased from 3520 mg per deciliter to 880 mg per deciliter, median hemoglobin levels increased from 10.5 g per deciliter to 13.8 g per deciliter, and bone marrow involvement decreased from 60% to 25% ( $P < 0.01$  for all comparisons). The median time to at least a minor response was 4 weeks. The overall response rate was 90.5%, and the major response rate was 73.0%; these rates were highest among patients with *MYD88*<sup>L265P</sup>*CXCR4*<sup>WT</sup> (with WT indicating wild-type) (100% overall response rate and 91.2% major response rate), followed by patients with *MYD88*<sup>L265P</sup>*CXCR4*<sup>WHIM</sup> (85.7% and 61.9%, respectively) and patients with *MYD88*<sup>WT</sup>*CXCR4*<sup>WT</sup> (71.4% and 28.6%). The estimated 2-year progression-free and overall survival rates among all patients were 69.1% and 95.2%, respectively. Treatment-related toxic effects of grade 2 or higher included neutropenia (in 22% of the patients) and thrombocytopenia (in 14%), which were more common in heavily pretreated patients; postprocedural bleeding (in 3%); epistaxis associated with the use of fish-oil supplements (in 3%); and atrial fibrillation associated with a history of arrhythmia (5%).

**CONCLUSIONS**

Ibrutinib was highly active, associated with durable responses, and safe in pretreated patients with Waldenström's macroglobulinemia. *MYD88* and *CXCR4* mutation status affected responses to this drug. (Funded by Pharmacyclics and others; ClinicalTrials.gov number, NCT01614821.)

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WALDENSTRÖM'S MACROGLOBULINEMIA is a malignant B-cell lymphoma that is associated with an accumulation of clonal lymphoplasmacytic cells and monoclonal IgM secretion.<sup>1</sup> Despite advances in treatment, the disease eventually progresses in most patients, and new treatment options are needed.

Whole-genome sequencing has revealed a single activating somatic mutation in *MYD88* (resulting in a predicted protein change from leucine to proline at amino acid position 265) and multiple activating mutations in the C-terminal domain of *CXCR4* in patients with Waldenström's macroglobulinemia.<sup>2,3</sup> In tumor cells, *MYD88*<sup>L265P</sup> triggers activation of nuclear factor  $\kappa$ B (NF- $\kappa$ B) through two divergent pathways involving Bruton's tyrosine kinase (BTK) and the interleukin-1 receptor–associated kinases (IRAK1 and IRAK4).<sup>4</sup>

Ibrutinib is an orally administered, small-molecule inhibitor of BTK that triggers apoptosis of Waldenström's macroglobulinemia cells with *MYD88*<sup>L265P</sup>. Clinical activity of ibrutinib in patients with Waldenström's macroglobulinemia was observed in a phase 1 study.<sup>4,5</sup>

Activating *CXCR4* somatic mutations in Waldenström's macroglobulinemia are similar to germline mutations detected in patients with the WHIM syndrome (warts, hypogammaglobulinemia, infections, and myelokathexis).<sup>6</sup> At least 30 different *CXCR4*<sup>WHIM</sup> somatic mutations are present in Waldenström's macroglobulinemia.<sup>3,7</sup> Tumor cells engineered to express *CXCR4*<sup>WHIM</sup> receptors have been shown to have enhanced CXCL12-triggered activation of the prosurvival factors AKT and extracellular signal-regulated kinase (ERK) and decreased in vitro ibrutinib-related apoptosis.<sup>8-10</sup>

In Waldenström's macroglobulinemia, three genomic groups (*MYD88*<sup>L265P</sup>*CXCR4*<sup>WT</sup> [with WT indicating wild-type], *MYD88*<sup>L265P</sup>*CXCR4*<sup>WHIM</sup>, and *MYD88*<sup>WT</sup>*CXCR4*<sup>WT</sup>) have been delineated on the basis of clinical manifestations and survival. These findings affirm an important role for *MYD88* and *CXCR4* somatic mutations in the pathogenesis of tumors.<sup>7</sup>

We performed a prospective, multicenter study of ibrutinib. We assessed safety and efficacy, as well as the influence of *MYD88* and *CXCR4* mutations on responses, in patients who had received previous treatment for Waldenström's macroglobulinemia.

## METHODS

### STUDY OVERSIGHT AND DESIGN

We conducted this study at three sites (the Dana-Farber Cancer Institute, Memorial Sloan Kettering Cancer Center, and Stanford University Medical Center). Enrollment began on May 23, 2012, and closed on June 13, 2013. The last patient evaluation and survival update occurred on December 19, 2014. All patients provided written informed consent after approval of the study by the institutional review boards at the three study sites.

Pharmacyclics and Janssen Pharmaceuticals supported this investigator-initiated study and provided research funding and the study drug. The first author designed the study, and all the authors vouch for the integrity of the data and adherence to the protocol (available with the full text of this article at NEJM.org). No one who is not an author contributed to the manuscript. The first author wrote all drafts of the manuscript. The academic authors administered the study drugs to the patients and collected the study data. The academic authors and Pharmacyclics coordinated the study, provided regulatory oversight, and analyzed the study data.

The primary objective was to determine the overall response rate, which included the rate of a minor response ( $\geq 25\%$  reduction in serum IgM levels), partial response ( $\geq 50\%$  reduction), very good partial response ( $\geq 90\%$  reduction), and complete response, and to determine the rate of major response (a complete response or responses with a  $\geq 50\%$  reduction in serum IgM levels).<sup>11</sup> Secondary objectives included the determination of progression-free survival and drug safety.

Serum IgM and complete blood counts were obtained at the beginning of each cycle for 3 cycles and thereafter every 3 cycles. Bone marrow biopsies and computed tomography (CT) (if extramedullary disease was present at baseline) were repeated at cycles 6, 12, and 24, and annually thereafter. CT assessments were performed locally with the use of bidimensional (long-axis and short-axis) serial measurements of representative nodes.

### PATIENTS

Eligibility criteria were the following: a need for treatment according to consensus guidelines, prior receipt of one or more treatment regimens, a platelet count of 50,000 per cubic millimeter or higher, a hemoglobin level of 8 g per deciliter or higher, an absolute neutrophil count of 1000 per cubic milli-

meter or higher, a serum creatinine level of 2 mg per deciliter or less, a total bilirubin level of 1.5 mg per deciliter or less (or <2 mg per deciliter if the level was attributable to the tumor), serum aspartate and alanine aminotransferase levels 2.5 times the upper limit of the normal range or less, and an Eastern Cooperative Oncology Group (ECOG) performance-status score of 2 or lower (on a scale of 0 to 5, with 0 indicating no symptoms and higher numbers indicating increasing tumor-related disability).<sup>1,12</sup> Patients were excluded if they had central nervous system lymphoma or clinically significant cardiovascular disease, if they were receiving warfarin, or if they were receiving medications that could prolong the QT interval.

The treatment regimen consisted of daily oral ibrutinib (at a dose of 420 mg) for twenty-six 4-week cycles until the disease progressed or unacceptable toxic effects developed. According to an amendment to the study protocol, patients without disease progression could provide a second informed consent and continue therapy beyond 26 cycles.

Ibrutinib was withheld if the following hematologic toxic effects occurred: a neutrophil count of less than 500 per cubic millimeter or a platelet count of less than 25,000 per cubic millimeter or less than 50,000 per cubic millimeter with bleeding. In addition, ibrutinib was withheld if the patient had nausea of grade 3 or higher, vomiting or diarrhea, or nonhematologic toxic effects of grade 3 or higher. Filgrastim therapy or transfusions were permitted. After ibrutinib was withheld the first time, full-dose retreatment was permitted after the patient recovered from toxic effects. Thereafter, reductions in the dose to 280 mg and then to 140 mg and, finally, discontinuation of the study drug were required as subsequent events occurred. In an amendment to the study protocol, it was recommended that to minimize the risk of bleeding, the drug should be withheld for 3 to 7 days before and for 1 to 3 days after an anticipated invasive procedure.

#### MYD88<sup>L265P</sup> AND CXCR4<sup>WHIM</sup> MUTATION GENOTYPING

An allele-specific polymerase-chain-reaction (PCR) assay was used to detect MYD88<sup>L265P</sup> mutations. CXCR4<sup>WHIM</sup> mutation status was determined by means of Sanger sequencing, and allele-specific PCR was used to detect CXCR4<sup>S338X</sup> C→G and C→A mutations in CD19-selected bone marrow cells.<sup>3,7,13,14</sup>

#### STATISTICAL ANALYSIS

A Simon's two-stage design was used with an alpha level set at 0.05 and a beta level set at 0.20; this assumed a null response rate of 20% and a successful overall response rate of 40% on the basis of comparisons with other monotherapies used in patients with previously treated Waldenström's macroglobulinemia. The protocol was amended according to regulatory guidance to require the enrollment of additional participants on the assumption that if the response rate for ibrutinib was 50%, the study would have more than 80% power to show a lower boundary of the two-sided 95% confidence interval for the response rate that would exceed 32%.

Responses were defined according to criteria adopted from the Third International Workshop on Waldenström's Macroglobulinemia.<sup>11</sup> Progression-free survival was defined as the time between the initiation of therapy and the date of disease progression, death, or last follow-up. The Kaplan–Meier method was used for time-to-event analyses with censoring. Pairwise comparisons were made with the use of a Wilcoxon rank-sum test with Bonferroni–Holm correction for multiple hypothesis testing. A Pearson correlation coefficient was used for linear comparisons. P values of 0.05 or less were considered to indicate statistical significance. Statistical analyses were performed with the use of SAS software, version 9.3 (SAS Institute).

## RESULTS

#### PATIENTS AND DISEASE CHARACTERISTICS

A total of 63 consecutive eligible patients (43 at the Dana–Farber Cancer Institute, 10 at Memorial Sloan Kettering Cancer Center, and 10 at Stanford University Medical Center) were enrolled. An independent, central pathology review confirmed that all the patients met the diagnostic criteria for Waldenström's macroglobulinemia.<sup>1</sup> The baseline characteristics of the patients are listed in Table 1.

MYD88<sup>L265P</sup> tumor mutation status was determined in all 63 patients, and CXCR4<sup>WHIM</sup> tumor mutation status was determined in 62 patients. MYD88<sup>L265P</sup> was present in 56 patients (89%), and CXCR4<sup>WHIM</sup> was present in 21 patients (34%). CXCR4<sup>WHIM</sup> mutations included nonsense mutations (16 CXCR4<sup>S338X</sup> and 2 CXCR4<sup>R334X</sup>) and frameshift mutations (1 S324fs and 2 S338fs). All patients with wild-type MYD88 had wild-type CXCR4, a finding consistent with prior findings.<sup>3,7</sup> No significant baseline differences according to MYD88 or

**Table 1. Baseline Characteristics of the Patients.\***

| Characteristic                                                             | Patients (N=63)          |
|----------------------------------------------------------------------------|--------------------------|
| Median age (range) — yr                                                    | 63 (44–86)               |
| Sex — no.                                                                  |                          |
| Male                                                                       | 48                       |
| Female                                                                     | 15                       |
| Median time from diagnosis of Waldenström's macroglobulinemia (range) — mo | 76 (6–340)               |
| Previous therapy for Waldenström's macroglobulinemia                       |                          |
| Median no. of previous treatment regimens (range)                          | 2 (1–9)                  |
| Type of therapy — no. (%)                                                  |                          |
| Monoclonal antibody                                                        | 57 (90)                  |
| Glucocorticoid                                                             | 42 (67)                  |
| Proteasome inhibitor                                                       | 33 (52)                  |
| Alkylator                                                                  | 32 (51)                  |
| Nucleoside analogue                                                        | 15 (24)                  |
| MTOR inhibitor                                                             | 13 (21)                  |
| Immunomodulator                                                            | 7 (11)                   |
| Anthracycline                                                              | 7 (11)                   |
| Autologous transplantation                                                 | 4 (6)                    |
| Other, including experimental therapy                                      | 13 (21)                  |
| Disease refractory to most recent regimen                                  | 25 (40)                  |
| Waldenström's macroglobulinemia IPSS score — no. (%)†                      |                          |
| Low                                                                        | 14 (22)                  |
| Intermediate                                                               | 27 (43)                  |
| High                                                                       | 22 (35)                  |
| Serum antibody levels                                                      |                          |
| IgM                                                                        |                          |
| Median (range) — mg/dl                                                     | 3520 (724–8390)          |
| >4000 mg/dl — no. (%)                                                      | 26 (41)                  |
| Median IgA (range) — mg/dl                                                 | 26 (0–125)               |
| Median IgG (range) — mg/dl                                                 | 381 (49–2770)            |
| Median absolute neutrophil count (range) — per mm <sup>3</sup>             | 3.18 (1.14–10.97)        |
| Hemoglobin level                                                           |                          |
| Median (range) — g/dl                                                      | 10.5 (8.2–13.8)          |
| <11 g/dl — no. (%)                                                         | 37 (59)                  |
| <10 g/dl — no. (%)                                                         | 25 (40)                  |
| Median hematocrit (range) — (%)                                            | 30.8 (24.5–41.5)         |
| Platelet count                                                             |                          |
| Median (range) — per mm <sup>3</sup>                                       | 214,000 (24,000–459,000) |
| <100,000/mm <sup>3</sup> — no. (%)                                         | 7 (11)                   |
| Serum $\beta_2$ -microglobulin                                             |                          |
| Median (range) — mg/liter                                                  | 3.9 (1.3–14.2)           |
| >3 mg/liter — no. (%)                                                      | 45 (71)                  |
| >3.5 mg/liter — no. (%)                                                    | 35 (56)                  |
| Adenopathy $\geq 1.5$ cm — no. (%)                                         | 37 (59)                  |
| Splenomegaly $\geq 15$ cm — no. (%)                                        | 7 (11)                   |
| Median bone marrow involvement (range) — %                                 | 60 (3–95)                |

\* IPSS denotes International Prognostic Scoring System, and mTOR mammalian target of rapamycin.

† The Waldenström's macroglobulinemia International Prognostic Scoring System (IPSS) to assess the risk of death is based on five adverse covariates: advanced age (>65 years), a hemoglobin level of 11.5 g per deciliter or more, a platelet count of 100,000 per cubic millimeter or less, a  $\beta_2$ -microglobulin level higher than 3 mg per liter, and a serum monoclonal protein concentration higher than 7.0 g per deciliter. Low-risk patients do not have advanced age and have either no adverse covariates or one adverse covariate, intermediate-risk patients have two adverse covariates or only advanced age, and high-risk patients have more than two adverse covariates.

CXCR4 mutation status were observed, except for a higher incidence of adenopathy among patients with wild-type CXCR4 than among those with CXCR4<sup>WHIM</sup> (68.3% vs. 33.3%,  $P=0.01$ ), a finding consistent with previous observations.<sup>7</sup> The median duration of treatment was 19.1 months (range, 0.5 to 29.7).

## RESPONSES

The median serum IgM level decreased from 3520 mg per deciliter to 880 mg per deciliter at the time of best response in the 63 patients overall ( $P<0.001$ ). Before therapy, 46 of the 63 patients (73%) had a serum IgM level of 3000 mg per deciliter or higher; after treatment, at the time of best response, 6 of the 63 patients (10%) had a serum IgM level of 3000 mg per deciliter or higher ( $P<0.001$ ).

Median bone marrow involvement decreased from 60% to 25% ( $P<0.001$ ), and the median hemoglobin level increased from 10.5 g per deciliter to 13.8 g per deciliter at the time of best response ( $P<0.001$ ). Discordance between serum IgM levels and bone marrow involvement was observed at 6 months ( $r=0.03$ ,  $P=0.83$ ), though by 12 months ( $r=0.51$ ,  $P<0.001$ ) and 24 months ( $r=0.56$ ,  $P<0.008$ ), a stronger correlation of these variables was evident.

Responses included a very good partial response in 10 patients, a partial response in 36 patients, and a minor response in 11 patients, representing overall and major responses of 90.5% (95% confidence interval [CI], 80.4 to 96.4) and 73.0% (95% CI, 60.3 to 83.4), respectively. The median times to at least minor and partial responses were 4 weeks and 8 weeks, respectively.

The rate of overall response was similar regardless of baseline age ( $<65$  vs.  $\geq 65$  years), ECOG performance-status score (0 vs.  $\geq 1$ ), pretherapy International Prognostic Scoring System (IPSS) score for patients with Waldenström's macroglobulinemia (see Table S1 in the Supplementary Appendix, available at NEJM.org),<sup>15</sup> serum  $\beta_2$ -microglobulin level ( $\leq 3$  vs.  $>3$  mg per liter), hemoglobin level ( $<11$  vs.  $\geq 11$  g per deciliter), serum IgM level ( $<4000$  vs.  $\geq 4000$  mg per deciliter), bone marrow involvement ( $<50\%$  vs.  $\geq 50\%$ ), prior relapsed or refractory disease, and the number of previous treatment regimens (1 to 3 vs.  $>3$ ). The rate of major response was also similar across most of the baseline subgroups (Fig. 1A and 1B), and rate of response was similar across the three participating institutions.

Overall and major response rates were highest

among patients with the MYD88<sup>L265P</sup>CXCR4<sup>WT</sup> genotype (100.0% and 91.2%, respectively), followed by MYD88<sup>L265P</sup>CXCR4<sup>WHIM</sup> (85.7% and 61.9%) and MYD88<sup>WT</sup>CXCR4<sup>WT</sup> (71.4% and 28.6%) (Fig. 1A and 1B). Improvements in overall and major response rates occurred in all three genomic subgroups with prolonged therapy ( $>6$  cycles) but were more pronounced among patients with MYD88<sup>L265P</sup>CXCR4<sup>WHIM</sup> mutations (Fig S1 in the Supplementary Appendix). Best serum IgM (Fig. 2A) and hemoglobin (Fig. 2B) responses were also influenced by tumor genotype; improvements were most evident in patients with MYD88<sup>L265P</sup>CXCR4<sup>WT</sup> and least evident in those with MYD88<sup>WT</sup>CXCR4<sup>WT</sup>.

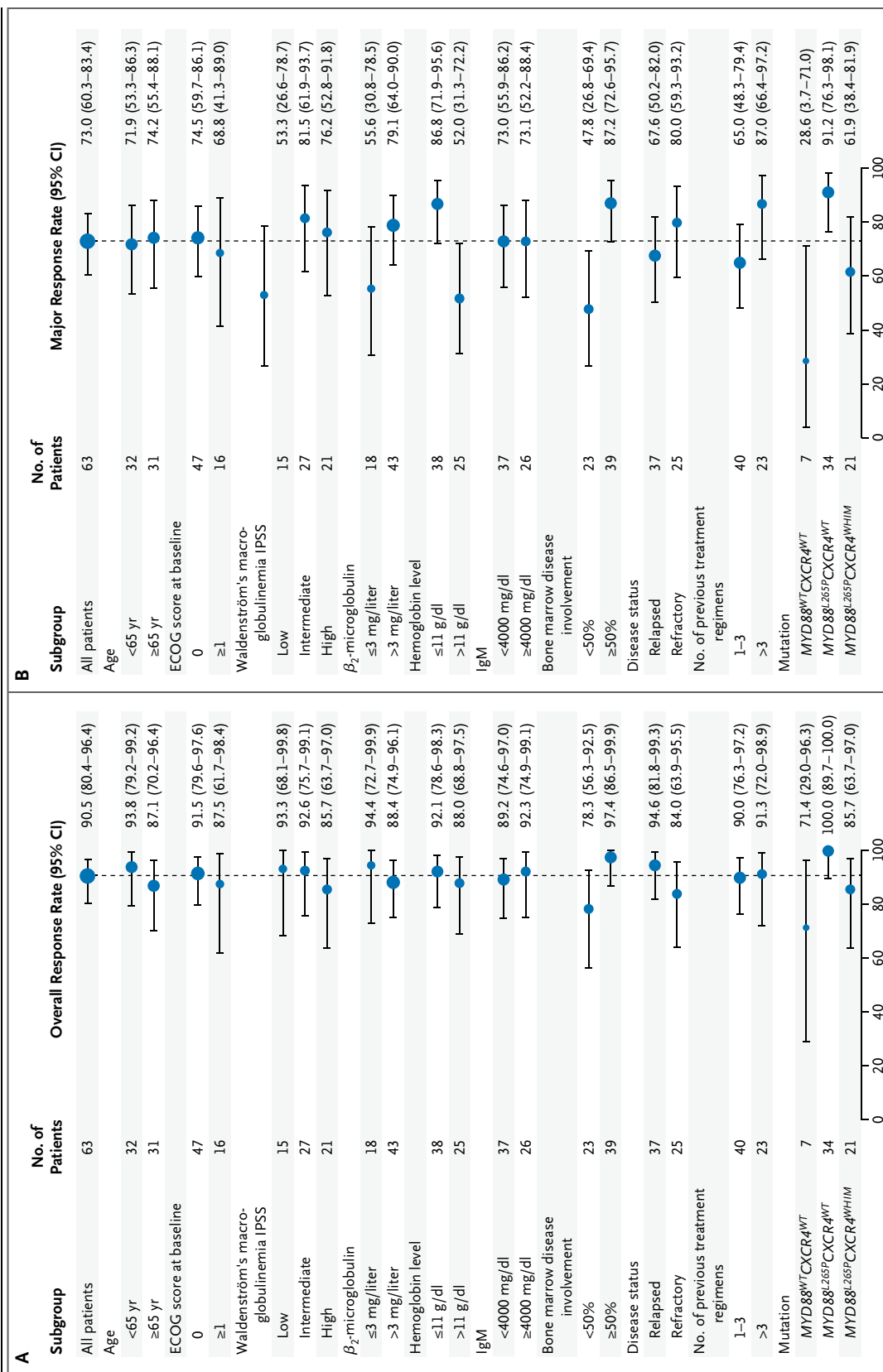
CT-identified adenopathy ( $\geq 1.5$  cm) was present in 37 patients at baseline. Serial imaging in 35 patients showed decreased or resolved adenopathy in 25 patients (68%), stable adenopathy in 9 patients (24%), and increased adenopathy in 1 patient (3%). Two patients discontinued the study before repeat imaging was required.

Among 7 patients with CT-identified splenomegaly ( $\geq 15$  cm), spleen size was decreased in 4 patients (57%), stable in 2 patients (29%), and could not be evaluated in 1 patient (14%) after elective splenectomy. Nine patients (14%), 3 of whom had anti-myelin-associated glycoprotein antibodies, received ibrutinib for progressive IgM-related peripheral sensory neuropathy. All 9 patients had a response, and subjective improvements in peripheral sensory neuropathy occurred in 5 patients and remained stable in 4 patients during the treatment course.

Symptomatic hyperviscosity related to progressive disease that necessitated plasmapheresis prompted the initiation of ibrutinib in 4 patients. All had a response, and none required additional plasmapheresis by the end of cycle 2. One patient required plasmapheresis for acquired factor VIII deficiency. He had a response and did not require further plasmapheresis. The spontaneous bleeding events that prompted therapy also resolved, and he continued to receive ibrutinib.

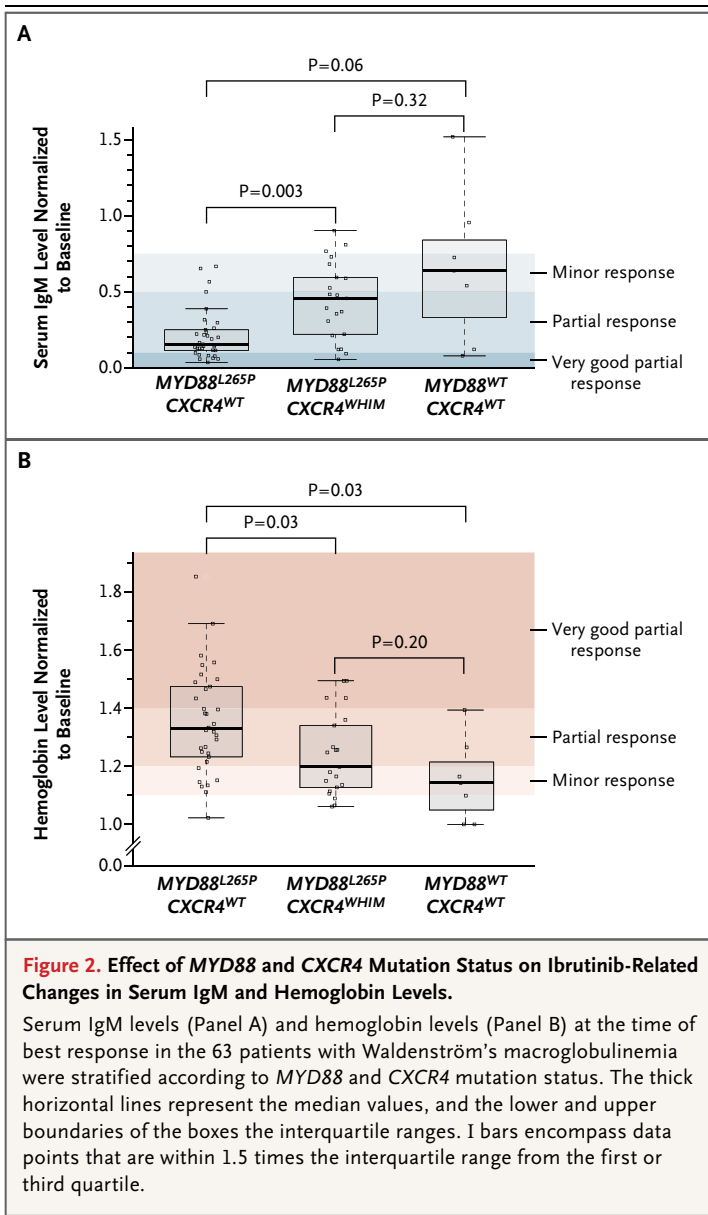
## TREATMENT PERIOD

The median duration of treatment was 19.1 months (range, 0.5 to 29.7); 43 patients (68%) continued to receive therapy after the database was locked (on December 19, 2014). Reasons for discontinuation of treatment included nonresponse (1 patient), progressive disease (7 patients), treatment-aggravated thrombocytopenia (1 pa-



**Figure 1. Subgroup Analyses of Responses.**

Subgroup analyses of overall responses (Panel A) and major responses (Panel B) are shown. Eastern Cooperative Oncology Group (ECOG) performance-status scores range from 0 to 5, with 0 indicating no symptoms and higher numbers indicating increasing tumor-related disability. The Waldenström's macroglobulinemia International Prognostic Scoring System (IPSS) to assess the risk of death is based on five adverse covariates: advanced age (>65 years), a hemoglobin level of 11.5 g per deciliter or more, a platelet count of 100,000 per cubic millimeter or less, a  $\beta_2$ -microglobulin level higher than 3 mg per liter, and a serum monoclonal protein concentration higher than 7.0 g per deciliter. Low-risk patients do not have advanced age and have either no adverse covariates or one adverse covariate; intermediate-risk patients have two adverse covariates or only advanced age; and high-risk patients have more than two adverse covariates. Bone marrow disease involvement was determined by means of direct morphologic assessment after hematocytin and eosin staining of a histopathological section and enumeration of lymphoplasmacytic cells occupying the intertrabecular space on complete representative slides.



tient), hematoma after bone marrow biopsy (1 patient), prolonged withholding of the drug because of infection unrelated to ibrutinib (1 patient), myelodysplasia and acute myeloid leukemia associated with baseline 5q deletion related to prior therapies (1 patient), disease transformation possibly related to prior nucleoside analogue therapy (2 patients), antineoplastic therapy for rectal carcinoma (1 patient), ibrutinib-incompatible medication (1 patient), the patient's decision to use commercially sourced ibrutinib (2 patients), travel difficulties (1 patient), and alternative therapy (1 patient).

#### PROGRESSION-FREE AND OVERALL SURVIVAL

Of the 63 patients enrolled, 60 patients were alive on the date on which the database was locked. Kaplan-Meier curves for progression-free survival among all 63 patients are shown in Figure 3A and for overall survival in Figure 3B. At 24 months, the estimated rate of progression-free survival was 69.1% (95% CI, 53.2 to 80.5), and the estimated rate of overall survival was 95.2% (95% CI, 86.0 to 98.4). Among patients with progressive disease, the median time to progression was 9.6 months (range, 3.5 to 19.4) if data on transformation events were censored, and 9.5 months (range, 3.5 to 19.4) if data on transformation events were included. Subgroup analysis showed that a high IPSS score before therapy, more than three previous treatment regimens, and a MYD88<sup>WT</sup> CXCR4<sup>WT</sup> genotype were associated with lower rates of progression-free survival (Fig. S2 in the Supplementary Appendix).

#### TOXIC EFFECTS

Grade 2 or higher treatment-related toxic effects are listed in Table 2. Neutropenia of grade 3 or higher occurred in 9 patients (14%), 7 of whom (78%) had received three or more prior therapies (P=0.05). Thrombocytopenia of grade 3 or higher occurred in 8 patients (13%), 7 of whom (88%) had received three or more prior therapies (P=0.01). Ibrutinib-related neutropenia and thrombocytopenia were reversible, although they necessitated dose reduction in 3 patients and treatment discontinuation in 4 patients.

Grade 2 or higher bleeding events occurred in 4 patients (2 of whom had epistaxis and 2 of whom had postprocedural bleeding before the study was amended to mandate withholding times for ibrutinib). Fish-oil supplements contributed to both grade 2 epistaxis events, and these events resolved when these supplements were discontinued.

Infections that were at least possibly associated with ibrutinib were few, and in most cases, patients with infections had preexisting IgA and IgG hypogammaglobulinemia. One patient with IgA and IgG hypogammaglobulinemia had streptococcal bacteremia and uncomplicated endocarditis after a dental procedure.

Atrial fibrillation related to ibrutinib occurred in 3 patients, all of whom had a history of paroxysmal atrial fibrillation. Atrial fibrillation resolved after ibrutinib was withheld, without cardiologic intervention, and protocol therapy resumed uneventfully in all 3 patients. Dose reductions due to toxic

effects, which occurred in 10 patients, did not influence responses or progression-free survival.

#### EFFECT OF IBRUTINIB ON PERIPHERAL LYMPHOCYTOSIS

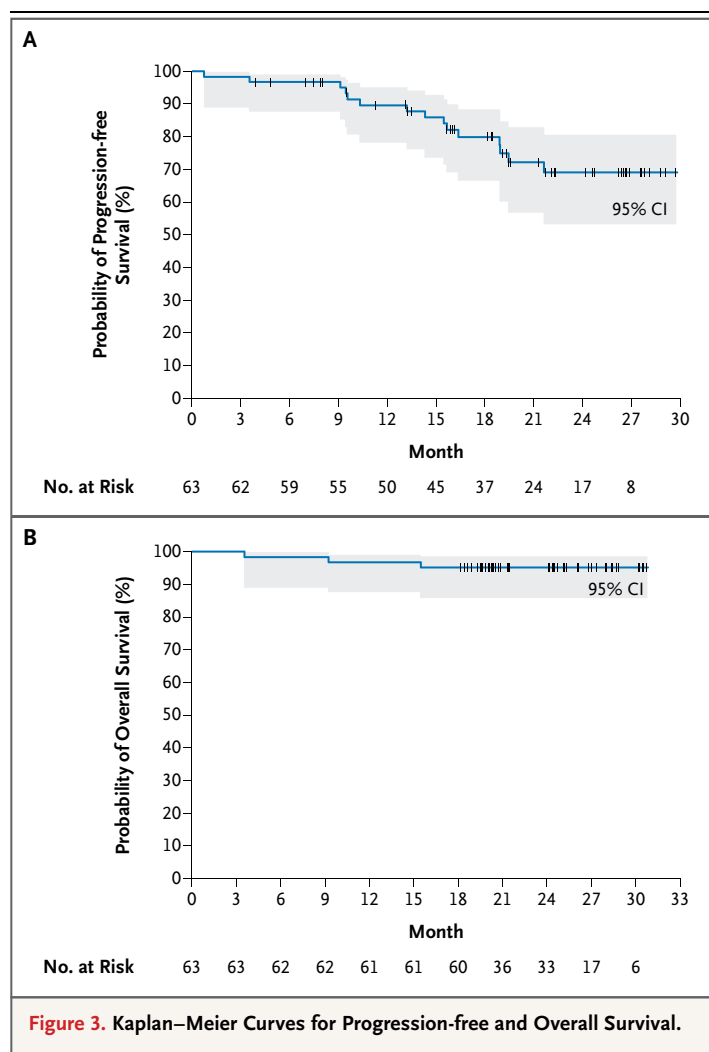
Since transduction through the CXCR4 receptor promotes bone marrow homing of Waldenström's macroglobulinemia cells,<sup>16</sup> we next examined the influence of MYD88 and CXCR4 mutation status on ibrutinib-related peripheral lymphocytosis. This influence was previously observed in chronic lymphoid leukemia and mantle-cell lymphoma.<sup>17-20</sup>

At baseline, patients with MYD88<sup>L265P</sup>CXCR4<sup>WT</sup>, MYD88<sup>L265P</sup>CXCR4<sup>WHIM</sup>, and MYD88<sup>WT</sup>CXCR4<sup>WT</sup> had similar levels of low circulating lymphocytes ( $P=0.74$  for the comparison of MYD88<sup>L265P</sup>CXCR4<sup>WT</sup> vs. MYD88<sup>L265P</sup>CXCR4<sup>WHIM</sup>,  $P=0.79$  for the comparison of MYD88<sup>L265P</sup>CXCR4<sup>WT</sup> vs. MYD88<sup>WT</sup>CXCR4<sup>WT</sup>, and  $P=0.92$  for the comparison of MYD88<sup>L265P</sup>CXCR4<sup>WHIM</sup> vs. MYD88<sup>WT</sup>CXCR4<sup>WT</sup>). Increases in median absolute lymphocyte levels were more pronounced within the first 6 months after the initiation of ibrutinib therapy in patients with MYD88<sup>L265P</sup>CXCR4<sup>WT</sup> than in patients with MYD88<sup>L265P</sup>CXCR4<sup>WHIM</sup> ( $P=0.04$ ).

Patients with MYD88<sup>WT</sup>CXCR4<sup>WT</sup> who typically have peripheral lymphocytosis had intermediate levels of increased peripheral lymphocytosis as compared with patients with MYD88<sup>L265P</sup>CXCR4<sup>WT</sup> and MYD88<sup>L265P</sup>CXCR4<sup>WHIM</sup> (Fig. S3A in the Supplementary Appendix) ( $P$  not significant). Higher levels of peripheral lymphocytosis were also observed in patients who had major (partial or very good partial) responses (Fig. S3B in the Supplementary Appendix) ( $P=0.01$ ).

#### DISCUSSION

The high prevalence of MYD88<sup>L265P</sup> in Waldenström's macroglobulinemia and its influence on tumor-cell survival through BTK-triggered NF- $\kappa$ B activation prompted us to perform this prospective, multicenter study of ibrutinib in previously treated patients with Waldenström's macroglobulinemia.<sup>2-4,21,22</sup> A high overall response rate (90.5%) and major response rate (73.0%) were observed among participants who had received a median of two prior therapies, and 40% of these patients had disease that was refractory to previous therapy. Moreover, at 2 years, the progression-free survival rate was 69.1% and the overall survival rate was 95.2%. By comparison, response rates of 40 to 80% with a median progression-free survival of 8 to 20 months have been reported with other



monotherapies in patients with relapsed or refractory Waldenström's macroglobulinemia.<sup>23,24</sup>

Ibrutinib, as compared with most other available therapies, also showed rapid response kinetics, with a median time to response of 4 weeks. Among patients who had a response, the median hemoglobin level increased from 10.3 g per deciliter at baseline to 11.4 g per deciliter at 4 weeks and 12.0 g per deciliter at 8 weeks. Improvements in serum IgM and hemoglobin levels occurred even in patients with modest or no changes in bone marrow disease burden; this suggests that a mechanism other than tumor debulking could contribute to the clinical benefit with ibrutinib in patients with Waldenström's macroglobulinemia.

Discordance between serum IgM levels and marrow disease burden has been reported with other therapeutic agents in Waldenström's macroglobulinemia.<sup>25-28</sup> The BTK substrate STAT5A regu-

**Table 2. Adverse Events Associated with Ibrutinib Therapy.\***

| Event or Abnormality                             | Grade 2 | Grade 3 | Grade 4 | Total Grades 2–4 |
|--------------------------------------------------|---------|---------|---------|------------------|
| <i>number of patients (percent)</i>              |         |         |         |                  |
| Blood and lymphatic system disorders             |         |         |         |                  |
| Neutropenia                                      | 5 (8)   | 6 (10)  | 3 (5)   | 14 (22)          |
| Thrombocytopenia                                 | 1 (2)   | 6 (10)  | 2 (3)   | 9 (14)           |
| Anemia                                           | 3 (5)   | 1 (2)   | 0       | 4 (6)            |
| Febrile neutropenia                              | 0       | 0       | 1 (2)   | 1 (2)            |
| Cardiac disorders                                |         |         |         |                  |
| Atrial fibrillation                              | 2 (3)   | 1 (2)   | 0       | 3 (5)            |
| Sinus tachycardia                                | 1 (2)   | 0       | 0       | 1 (2)            |
| Gastrointestinal disorders                       |         |         |         |                  |
| Gastroesophageal reflux                          | 3 (5)   | 0       | 0       | 3 (5)            |
| Stomatitis                                       | 3 (5)   | 0       | 0       | 3 (5)            |
| Constipation                                     | 2 (3)   | 0       | 0       | 2 (3)            |
| Diarrhea                                         | 2 (3)   | 0       | 0       | 2 (3)            |
| Ulceration                                       | 2 (3)   | 0       | 0       | 2 (3)            |
| Infections and infestations                      |         |         |         |                  |
| Pneumonia                                        | 4 (6)   | 1 (2)   | 0       | 5 (8)            |
| Skin infection                                   | 3 (5)   | 0       | 0       | 3 (5)            |
| Cellulitis                                       | 1 (2)   | 0       | 0       | 1 (2)            |
| Herpes zoster                                    | 1 (2)   | 1 (2)   | 0       | 2 (3)            |
| Sinusitis                                        | 1 (2)   | 0       | 0       | 1 (2)            |
| Streptococcal endocarditis                       | 0       | 1 (2)   | 0       | 1 (2)            |
| Subcutaneous abscess                             | 1 (2)   | 1 (2)   | 0       | 1 (2)            |
| Urinary tract infection                          | 1 (2)   | 1 (2)   | 0       | 1 (2)            |
| Postprocedural complications                     |         |         |         |                  |
| Hematoma                                         | 0       | 1 (2)   | 0       | 1 (2)            |
| Hemorrhage                                       | 1 (2)   | 0       | 0       | 1 (2)            |
| Dehydration                                      | 2 (3)   | 0       | 0       | 2 (3)            |
| Musculoskeletal and connective-tissue disorders  |         |         |         |                  |
| Tendinitis                                       | 1 (2)   | 0       | 0       | 1 (2)            |
| Tenosynovitis                                    | 1 (2)   | 0       | 0       | 1 (2)            |
| Nervous system disorders                         |         |         |         |                  |
| Headache                                         | 1 (2)   | 0       | 0       | 1 (2)            |
| Presyncope                                       | 1 (2)   | 0       | 0       | 1 (2)            |
| Syncope                                          | 0       | 1 (2)   | 0       | 1 (2)            |
| Respiratory, thoracic, and mediastinal disorders |         |         |         |                  |
| Epistaxis                                        | 2 (3)   | 0       | 0       | 2 (3)            |
| Cough                                            | 1 (2)   | 0       | 0       | 1 (2)            |
| Skin and subcutaneous tissue disorders           |         |         |         |                  |
| Pruritus                                         | 1 (2)   | 0       | 0       | 1 (2)            |
| Rash                                             | 1 (2)   | 0       | 0       | 1 (2)            |
| Skin exfoliation                                 | 1 (2)   | 0       | 0       | 1 (2)            |
| Vascular disorders                               |         |         |         |                  |
| Hypertension                                     | 3 (5)   | 0       | 0       | 3 (5)            |
| Hypotension                                      | 1 (2)   | 0       | 0       | 1 (2)            |

\* Listed are adverse events that were deemed by the investigators to be possibly, probably, or definitely associated with the study drug.

lates IgM secretion in these tumor cells, and its selective inhibition by ibrutinib may have contributed to the early discordant findings.<sup>29,30</sup> Transient increases in serum IgM levels commonly occurred during periods in which the drug was withheld because of toxic effects or procedures, and these levels decreased with reinstitution of therapy.

Extramedullary disease was also affected by ibrutinib therapy; 68% of the patients had decreased or resolved adenopathy, and 57% had decreased splenomegaly on serial CT imaging. Resolution of malignant pleural effusions also occurred in 2 of 3 patients. Progressive IgM-related peripheral neuropathy prompted therapy in 9 patients who had previously received rituximab. Subjective improvement or stabilization of symptoms occurred during the course of treatment in these patients. These findings are particularly encouraging given the challenging nature of treating IgM-related peripheral neuropathy in Waldenström's macroglobulinemia.<sup>23,31</sup> Up to 25% of patients with Waldenström's macroglobulinemia have paraprotein-related peripheral neuropathy, and rituximab remains a mainstay of treatment. A recent placebo-controlled study showed no objective evidence of symptomatic improvement with the use of rituximab in patients with IgM-related peripheral neuropathy.<sup>32</sup> Moreover, rituximab can often cause a flare in serum IgM levels that can potentiate symptoms of peripheral neuropathy.<sup>23,24</sup> In our study, no IgM flare was observed in any of the 63 study patients who received ibrutinib.

Overall and major response rates were highest among patients with *MYD88*<sup>L265P</sup>*CXCR4*<sup>WT</sup> (100% and 91.2%, respectively), followed by those with *MYD88*<sup>L265P</sup>*CXCR4*<sup>WHIM</sup> (85.7% and 61.9%), and those with *MYD88*<sup>WT</sup>*CXCR4*<sup>WT</sup> (71.4% and 28.6%). Although these findings are based on a small cohort of patients with Waldenström's macroglobulinemia, they probably reflect BTK dependence on *MYD88*<sup>L265P</sup>-triggered signaling and intrinsic resistance conferred by *CXCR4*<sup>WHIM</sup> mutations in Waldenström's macroglobulinemia cells.<sup>2,4,8-10</sup> Furthermore, bone marrow homing of Waldenström's macroglobulinemia cells engineered to express the *CXCR4*<sup>S338X</sup> receptor could be inhibited by a *CXCR4*-blocking antibody; this is a relevant finding, since the bone marrow stroma protects the tumor cells against many therapeutic agents.<sup>10</sup> These insights may also help to explain why the incidence of ibrutinib-triggered peripheral lymphocytosis was higher among patients

with *MYD88*<sup>L265P</sup>*CXCR4*<sup>WT</sup> than among patients with *MYD88*<sup>L265P</sup>*CXCR4*<sup>WHIM</sup>. They may also account for the better categorical responses in patients with more pronounced peripheral lymphocytosis.

These findings are also likely to herald efforts to combine *CXCR4* antagonists with ibrutinib in patients with *CXCR4*<sup>WHIM</sup> mutations. Plerixafor, a *CXCR4* antagonist approved by the Food and Drug Administration for use in stem-cell mobilization, sensitizes Waldenström's macroglobulinemia cells engineered to express *CXCR4*<sup>WHIM</sup> receptors to undergo apoptosis in response to ibrutinib.<sup>8,9</sup> The feasibility of long-term use of plerixafor has been reported in patients with the WHIM syndrome, and clinical trials of other *CXCR4* inhibitors are ongoing.<sup>33</sup>

Improvements in overall and major responses occurred in all three genomic subgroups with prolonged therapy (>6 cycles) but were more pronounced in patients with *MYD88*<sup>L265P</sup>*CXCR4*<sup>WHIM</sup> mutations. A short course of *CXCR4* inhibition during the initial phase of ibrutinib therapy may therefore be sufficient to prompt earlier and deeper responses to ibrutinib in patients with Waldenström's macroglobulinemia who have *CXCR4* mutations.

Overall, toxic effects of treatment were moderate in this selected patient population. Heavily pretreated patients were more at risk for clinically significant neutropenia and thrombocytopenia than were patients with fewer previous treatment regimens. Four bleeding events were related to procedures or fish-oil supplements. Atrial fibrillation related to ibrutinib occurred in 3 patients (5%), all of whom had a history of arrhythmia, and atrial fibrillation reverted after ibrutinib was withheld. In a randomized study, atrial fibrillation was observed in 3% of patients with chronic lymphoid leukemia who received ibrutinib, as compared with no patients who received ofatumumab.<sup>34</sup> Few infections were associated with ibrutinib, and this drug did not significantly alter serum IgA and IgG levels (as was also observed in patients with chronic lymphoid leukemia and patients with mantle-cell lymphoma).<sup>17,18</sup> Collectively, safety, along with the IgA-sparing and IgG-sparing effects, distinguish ibrutinib from other salvage options in Waldenström's macroglobulinemia.<sup>23,24</sup>

In summary, ibrutinib was active in previously treated patients with Waldenström's macroglobulinemia. An overall response rate of 90.5%, and 2-year progression-free and overall survival rates of 69.1% and 95.2%, respectively, were achieved with

ibrutinib monotherapy. Responses to ibrutinib were influenced by *MYD88* and *CXCR4* mutation status. Overall, toxic effects of treatment were moderate, and no unexpected toxic effects were observed.

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