

ORIGINAL ARTICLE

Placebo-Controlled Phase 3 Study of Oral BG-12 for Relapsing Multiple Sclerosis

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ABSTRACT

BACKGROUND

BG-12 (dimethyl fumarate) was shown to have antiinflammatory and cytoprotective properties in preclinical experiments and to result in significant reductions in disease activity on magnetic resonance imaging (MRI) in a phase 2, placebo-controlled study involving patients with relapsing–remitting multiple sclerosis.

METHODS

We conducted a randomized, double-blind, placebo-controlled phase 3 study involving patients with relapsing–remitting multiple sclerosis. Patients were randomly assigned to receive oral BG-12 at a dose of 240 mg twice daily, BG-12 at a dose of 240 mg three times daily, or placebo. The primary end point was the proportion of patients who had a relapse by 2 years. Other end points included the annualized relapse rate, the time to confirmed progression of disability, and findings on MRI.

RESULTS

The estimated proportion of patients who had a relapse was significantly lower in the two BG-12 groups than in the placebo group (27% with BG-12 twice daily and 26% with BG-12 thrice daily vs. 46% with placebo, $P < 0.001$ for both comparisons). The annualized relapse rate at 2 years was 0.17 in the twice-daily BG-12 group and 0.19 in the thrice-daily BG-12 group, as compared with 0.36 in the placebo group, representing relative reductions of 53% and 48% with the two BG-12 regimens, respectively ($P < 0.001$ for the comparison of each BG-12 regimen with placebo). The estimated proportion of patients with confirmed progression of disability was 16% in the twice-daily BG-12 group, 18% in the thrice-daily BG-12 group, and 27% in the placebo group, with significant relative risk reductions of 38% with BG-12 twice daily ($P = 0.005$) and 34% with BG-12 thrice daily ($P = 0.01$). BG-12 also significantly reduced the number of gadolinium-enhancing lesions and of new or enlarging T_2 -weighted hyperintense lesions ($P < 0.001$ for the comparison of each BG-12 regimen with placebo). Adverse events associated with BG-12 included flushing and gastrointestinal events, such as diarrhea, nausea, and upper abdominal pain, as well as decreased lymphocyte counts and elevated liver aminotransferase levels.

CONCLUSIONS

In patients with relapsing–remitting multiple sclerosis, both BG-12 regimens, as compared with placebo, significantly reduced the proportion of patients who had a relapse, the annualized relapse rate, the rate of disability progression, and the number of lesions on MRI. (Funded by Biogen Idec; DEFINE ClinicalTrials.gov number, NCT00420212.)

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*The Determination of the Efficacy and Safety of Oral Fumarate in Relapsing–Remitting MS (DEFINE) study investigators are listed in the Supplementary Appendix, available at NEJM.org.

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ORAL BG-12 (DIMETHYL FUMARATE) IS being investigated for the treatment of multiple sclerosis. Inflammation and oxidative stress are central pathologic factors in multiple sclerosis.^{1,2} Immune cell activation and infiltration into the central nervous system are thought to result in widespread cellular damage, potentially owing to the dysregulated production and release of reactive oxygen and nitrogen species, such as hydrogen peroxide and peroxynitrite, and proinflammatory stimuli.³ This combination of toxic factors ultimately results in demyelination and neurodegeneration, causing disease activity and progression of disability.

BG-12 has been shown to have beneficial effects in preclinical models of neuroinflammation, neurodegeneration, and toxic oxidative stress, which appear to be mediated predominately through activation of the nuclear 1 factor (erythroid-derived 2)-like 2 (Nrf2) antioxidant response pathway, the primary cellular defense against the cytotoxic effects of oxidative stress.^{1,4} BG-12 may also play a role in modulating immune-cell responses by shifting dendritic-cell differentiation,⁵ suppressing proinflammatory-cytokine production, or directly inhibiting proinflammatory pathways.⁶

In a randomized, placebo-controlled, 24-week, phase 2 study involving patients with relapsing–remitting multiple sclerosis,⁷ BG-12, as compared with placebo, significantly reduced the number of new gadolinium-enhancing lesions, new or enlarging hyperintense lesions on T₂-weighted images, and new hypointense lesions on T₁-weighted images. Here, we report the results of the Determination of the Efficacy and Safety of Oral Fumarate in Relapsing–Remitting MS (DEFINE) study, in which two dose regimens of BG-12 were compared with placebo.

METHODS

STUDY OVERSIGHT

We conducted a randomized, double-blind, placebo-controlled, 2-year phase 3 study of BG-12 in patients with relapsing–remitting multiple sclerosis. Members of the advisory committee and the data and safety monitoring committee (see the Study Oversight section in the Supplementary Appendix, available with the full text of this article at NEJM.org) collaborated with the sponsor, Biogen Idec, to develop the protocol and monitor the ongoing study.

Data were collected by the investigators and were analyzed by the sponsor. The investigators and sponsor agreed to maintain data confidentiality during the study. All the authors had early access to the data, participated in person in the data analysis and interpretation, and vouch for the accuracy and completeness of the data and the statistical analysis and for the fidelity of the study to the protocol. The first draft of the manuscript was written by the first author and the senior author representing the sponsor, with support from medical writers from Infusion Communications, who were funded by the sponsor. All the authors participated in writing subsequent drafts of the manuscript and made the decision to submit it for publication. The protocol, including the statistical analysis plan, is available at NEJM.org; the study was conducted and reported as described in the protocol.

PATIENTS

Key eligibility criteria included an age of 18 to 55 years, a diagnosis of relapsing–remitting multiple sclerosis as defined according to the McDonald criteria,^{8,9} a baseline score of 0 to 5.0 on the Expanded Disability Status Scale (EDSS, which ranges from 0 to 10, with higher scores indicating greater disability),¹⁰ and disease activity as evidenced by at least one clinically documented relapse within 12 months before randomization or a brain magnetic resonance imaging (MRI) scan, obtained within 6 weeks before randomization, that showed at least one gadolinium-enhancing lesion. Key exclusion criteria were progressive forms of multiple sclerosis,⁹ another major disease that would preclude participation in a clinical trial, abnormal results on prespecified laboratory tests, or recent exposure to contraindicated medications (Table S1 in the Supplementary Appendix).

All patients were fully informed of approved therapies for multiple sclerosis as an alternative to participation in a placebo-controlled trial and provided written informed consent; we also obtained re-consent from patients after a confirmed relapse or progression of disability (after discussion of treatment options as detailed below). The study was approved by central and local ethics committees and was conducted in accordance with the International Conference on Harmonization Guidelines for Good Clinical Practice¹¹ and the Declaration of Helsinki.¹²

STUDY DESIGN

Patients at 198 sites in 28 countries were randomly assigned, in a 1:1:1 ratio, to receive, in a double-blind fashion, BG-12 at a dose of 240 mg twice daily, BG-12 at a dose of 240 mg three times daily, or placebo (Fig. S1 in the Supplementary Appendix). Randomization was performed centrally and was stratified according to site.

To maintain concealment of the study-group assignments, each study center used separate examining and treating neurologists (all of whom remained unaware of the assignments throughout the trial). The examining neurologists conducted neurologic assessments, including assessment of the EDSS score, whereas the treating neurologists were responsible for all aspects of patient care, including the treatment of relapses and other disease symptoms. To ensure that the study-group assignments would not be revealed, patients were instructed to take the assigned study drug at least 4 hours before study visits, in case patients in the BG-12 groups had a side effect of flushing.

All patients were eligible to switch to an alternative therapy for multiple sclerosis if they had completed 48 weeks of the study treatment and had had one or more confirmed relapses after 24 weeks; patients could switch at any time if they had confirmed progression of disability.

STUDY PROCEDURES AND END POINTS

Study visits were scheduled every 4 weeks for safety assessments, including the monitoring of laboratory values; for dispensing of the study drug; and for assessment of adherence to the study drug. During clinic visits every 12 weeks, standardized neurologic assessments, including assessment of the EDSS score, were performed by physicians who were certified either by in-person training or through an online program (www.Neurostatus.net). MRI scans were obtained at screening and at weeks 24, 48, and 96 in a subgroup of patients at sites with full MRI capabilities. All scans were evaluated in a blinded manner at a central reading facility (NeuroRx Research). Unscheduled visits were conducted as needed to evaluate suspected relapses.

The primary end point was the proportion of patients who had a relapse by 2 years. Protocol-defined relapses were new or recurrent neurologic symptoms, not associated with fever or infection, that lasted for at least 24 hours and that were accompanied by new objective neurologic findings

according to the examining neurologist's evaluation. All protocol-defined relapses were evaluated by an independent neurologic evaluation committee (see the Study Oversight section in the Supplementary Appendix), whose members reviewed a standardized set of blinded clinical records (which did not include MRI data) from the treating and examining neurologists.

Secondary end points at 2 years included the number of gadolinium-enhancing lesions and of new or enlarging hyperintense lesions on T₂-weighted images, the annualized relapse rate (the total number of relapses divided by the number of patient-years in the study, excluding data obtained after patients switched to alternative multiple sclerosis medications), and the time to progression of disability. Disability progression was defined as at least a 1.0-point increase on the EDSS in patients with a baseline score of 1.0 or higher or at least a 1.5-point increase in patients with a baseline score of 0, with the increased score sustained for at least 12 weeks.

STATISTICAL ANALYSIS

All efficacy analyses were performed on data from the intention-to-treat population, which included all patients who underwent randomization and who received at least one dose of the study drug. All statistical tests were two-sided, with an overall type I error rate of 0.05. Sensitivity analyses were performed on the primary end point.

On the basis of data from another clinical trial in which an active drug was compared with placebo in patients with multiple sclerosis,¹³ we estimated that 48.0% of patients receiving placebo and 33.6% of patients receiving BG-12 would have at least one relapse during the study. Using a chi-square test with a two-sided alpha level of 0.05, and assuming an estimated dropout rate of 23%, we estimated that we would need to enroll 337 patients in each group for the study to have 90% power to detect the 30% reduction in the percentage of patients with a relapse in each BG-12 group as compared with the placebo group. The primary end point was analyzed with the use of a Cox proportional-hazards model, adjusted for baseline EDSS score, age, region, and number of relapses in the year before study entry. The estimated proportion of patients with a relapse was derived with the use of the Kaplan–Meier product-limit method, which was based on the time-to-first-relapse survival distribution.

For secondary end points, the analyses were conducted in the following ranked order: an analysis of the number of new or newly enlarging hyperintense lesions on T₂-weighted images, with the use of a negative binomial model; an analysis of the number of gadolinium-enhancing lesions, with the use of an ordinal logistic-regression model; an analysis of the annualized relapse rate, with the use of a negative binomial regression model; and an analysis of the time to progression of disability that was sustained for 12 weeks, with the use of a Cox proportional-hazards model. The analytic models included adjustments for region and baseline characteristics, including EDSS score, age, relapse rate, and number or volume of baseline lesions, as appropriate.

A sequential (closed) testing procedure was used to control the overall type I error rate due to multiple comparisons. Formal testing of the comparison of twice-daily BG-12 with placebo was undertaken only if the comparison of thrice-daily BG-12 with placebo was significant ($P \leq 0.05$). Analysis of secondary end points, according to the ranked order, followed an additional sequential testing procedure such that if statistical significance was not achieved for an end point, all lower-ranking end points were also considered to be nonsignificant.

Among patients who switched to an alternative therapy for multiple sclerosis, all the data before the switch were used for the analysis of the clinical end points. For the analyses of MRI end points in these patients, the data before the switch were used and then data after the rescue therapy was initiated were imputed with the use of a constant rate assumption.

Safety analyses were summarized with the use of descriptive statistics for all patients who received at least one dose of the study drug. Among patients who switched to alternative medications, data collected after the switch were excluded from the safety analyses.

RESULTS

PATIENTS

A total of 1237 patients underwent randomization, of whom 1234 received at least one dose of the study drug (intention-to-treat population). The baseline demographic and disease characteristics were generally well balanced across the study groups (Table 1). Patients were 18 to 56 years of age and had received a diagnosis of multiple

sclerosis between 0 and 32 years before study entry. Approximately 40% of the patients had previously received approved therapies for relapsing-remitting multiple sclerosis (Table 1). A total of 540 patients were included in the subgroup of patients who underwent MRI. The baseline demographic and disease characteristics of patients in the MRI cohort were similar to those of patients who were not in the MRI cohort and to those of the overall study population (Table S2 in the Supplementary Appendix).

A total of 952 patients (77%) completed the study (78% in the placebo group and 77% in each of the BG-12 groups) (Fig. S2 in the Supplementary Appendix). The rate of discontinuation of the study drug was similar in the three groups (35% in the placebo group and 31% in each of the BG-12 groups), as was the rate of withdrawal from the study (22% in the placebo group and 23% in each of the BG-12 groups) (Table S3 and Fig. S2 in the Supplementary Appendix). The percentage of patients who switched to an approved therapy for multiple sclerosis was low (13% in the placebo group, 6% in the twice-daily BG-12 group, and 5% in the thrice-daily BG-12 group). The mean duration of participation in the study was 83.9 weeks and was similar among the three groups.

EFFICACY

Relapses

The proportion of patients who had at least one relapse of multiple sclerosis by 2 years was significantly reduced with each BG-12 regimen as compared with placebo. On the basis of Kaplan-Meier estimates, 27% of the patients in the twice-daily BG-12 group and 26% in the thrice-daily BG-12 group, as compared with 46% in the placebo group, had a relapse at 2 years ($P < 0.001$ for both comparisons) (Table 2 and Fig. 1A). The hazard ratio for the risk of relapse with BG-12 treatment as compared with placebo during the 2-year period was 0.51 for the twice-daily group (95% confidence interval [CI], 0.40 to 0.66) and 0.50 for the thrice-daily group (95% CI, 0.39 to 0.65) ($P < 0.001$ for both comparisons), corresponding to a 49% and 50% reduction, respectively, in the risk of relapse. Each BG-12 regimen, as compared with placebo, prolonged the time to a first relapse (time to relapse in the 25th percentile of patients, 38 weeks in the placebo group, as compared with 87 weeks and 91 weeks in the twice-daily and thrice-daily BG-12 groups, respective-

Table 1. Baseline Characteristics of the Intention-to-Treat Population.*

Characteristic	Placebo (N = 408)	Twice-Daily BG-12 (N = 410)	Thrice-Daily BG-12 (N = 416)
Age — yr	38.5±9.1	38.1±9.1	38.8±8.8
Female sex — no. (%)	306 (75)	296 (72)	306 (74)
Weight — kg	71.1±17.0	70.7±18.5	71.3±16.9
Race — no. (%)†			
White	318 (78)	321 (78)	330 (79)
Asian	42 (10)	38 (9)	36 (9)
Black	8 (2)	8 (2)	10 (2)
Other or unknown	40 (10)	43 (10)	40 (10)
Previous use of approved medication for multiple sclerosis — no. (%)‡	172 (42)	162 (40)	168 (40)
Time since diagnosis — yr	5.8±5.8	5.6±5.4	5.1±5.3
Relapses in previous 12 mo — no.	1.3±0.7	1.3±0.7	1.3±0.6
EDSS score at baseline — no. (%)§			
0	21 (5)	29 (7)	24 (6)
1.0 or 1.5	105 (26)	109 (27)	104 (25)
2.0 or 2.5	112 (27)	116 (28)	146 (35)
3.0 or 3.5	97 (24)	82 (20)	85 (20)
4.0 or 4.5	56 (14)	56 (14)	42 (10)
5.0	16 (4)	16 (4)	14 (3)
Mean score on EDSS	2.48±1.24	2.40±1.29	2.36±1.19
MRI findings¶			
Gadolinium-enhancing T ₁ -weighted lesions — no.	1.6±3.4	1.2±3.3	1.2±4.1
Hyperintense T ₂ -weighted lesions			
Mean no.	49.2±38.6	47.6±34.7	55.8±44.3
<9 — no. of patients	12	9	14
≥9 — no. of patients	168	167	170

* Plus-minus values are means ±SD. The intention-to-treat population included all patients who underwent randomization and received at least one dose of the study drug. All the baseline characteristics were well balanced among the study groups (nominal $P > 0.05$).

† Race was self-reported.

‡ Approved medications for multiple sclerosis include interferon beta-1a (used in 27% of all randomly assigned patients), glatiramer acetate (15%), interferon beta-1b (14%), and natalizumab (3%). Patients may have received more than one prior medication for multiple sclerosis. Patients may also have received other, nonapproved therapies for multiple sclerosis. (The percentage of patients receiving any medication for multiple sclerosis before study entry was 54 to 56% across treatment groups.)

§ Scores on the Expanded Disability Status Scale (EDSS) range from 0 to 10, with higher scores indicating a greater degree of disability. The baseline score was higher than 5.0 in one patient in each group, and the score was unknown for one patient in the twice-daily BG-12 group.

¶ Magnetic resonance imaging (MRI) was performed in 180 patients in the placebo group, 176 in the twice-daily BG-12 group, and 184 in the thrice-daily BG-12 group.

ly). Sensitivity analyses, performed with the use of logistic regression, in which patients who discontinued the study drug or withdrew from the study without having had a relapse were considered to have had a relapse if the reason for discontinuation or withdrawal was suggestive of a lack of efficacy, showed that BG-12 treatment also reduced the proportion of patients who had a relapse by 2 years (odds ratio for relapse, 0.42 with twice-daily BG-12 and 0.41 with thrice-daily BG-12; $P < 0.001$ for both comparisons). An additional sensitivity analysis that included all proto-

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