Terminal Complement Inhibitor Eculizumab in Atypical Hemolytic-Uremic Syndrome


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Terminal Complement Inhibitor Eculizumab in Atypical Hemolytic–Uremic Syndrome


ABSTRACT

BACKGROUND
Atypical hemolytic–uremic syndrome is a genetic, life-threatening, chronic disease of complement-mediated thrombotic microangiopathy. Plasma exchange or infusion may transiently maintain normal levels of hematologic measures but does not treat the underlying systemic disease.

METHODS
We conducted two prospective phase 2 trials in which patients with atypical hemolytic–uremic syndrome who were 12 years of age or older received eculizumab for 26 weeks and during long-term extension phases. Patients with low platelet counts and renal damage (in trial 1) and those with renal damage but no decrease in the platelet count of more than 25% for at least 8 weeks during plasma exchange or infusion (in trial 2) were recruited. The primary end points included a change in the platelet count (in trial 1) and thrombotic microangiopathy event–free status (no decrease in the platelet count of >25%, no plasma exchange or infusion, and no initiation of dialysis) (in trial 2).

RESULTS
A total of 37 patients (17 in trial 1 and 20 in trial 2) received eculizumab for a median of 64 and 62 weeks, respectively. Eculizumab resulted in increases in the platelet count; in trial 1, the mean increase in the count from baseline to week 26 was 73×10⁹ per liter (P<0.001). In trial 2, 80% of the patients had thrombotic microangiopathy event–free status. Eculizumab was associated with significant improvement in all secondary end points, with continuous, time-dependent increases in the estimated glomerular filtration rate (GFR). In trial 1, dialysis was discontinued in 4 of 5 patients. Earlier intervention with eculizumab was associated with significantly greater improvement in the estimated GFR. Eculizumab was also associated with improvement in health-related quality of life. No cumulative toxicity of therapy or serious infection-related adverse events, including meningococcal infections, were observed through the extension period.

CONCLUSIONS
Eculizumab inhibited complement-mediated thrombotic microangiopathy and was associated with significant time-dependent improvement in renal function in patients with atypical hemolytic–uremic syndrome. (Funded by Alexion Pharmaceuticals; C08-002 ClinicalTrials.gov numbers, NCT00844545 [adults] and NCT00844844 [adolescents]; C08-003 ClinicalTrials.gov numbers, NCT00838513 [adults] and NCT00844428 [adolescents]).
A typical hemolytic–uremic syndrome is a genetic, chronic, and progressive inflammatory disease that affects patients of all ages. This syndrome is caused by defects in regulation of the complement system. These defects are inherited, acquired, or both, and they result in chronic, uncontrolled activation of the complement system which leads to platelet, leukocyte, and endothelial-cell activation and systemic thrombotic microangiopathy. Affected patients have a lifelong risk of systemic clinical complications of thrombotic microangiopathy, including damage to multiple organ systems (e.g., the central nervous system, kidneys, heart, and gastrointestinal tract).

Although plasma exchange or infusion has been used to manage atypical hemolytic–uremic syndrome and may transiently maintain a normal platelet count and lactate dehydrogenase level in some patients, the underlying complement dysregulation and thrombotic microangiopathic processes are likely to persist. Indeed, end-stage renal disease (ESRD) or death occurs in approximately 33 to 40% of patients during the first clinical manifestation of atypical hemolytic–uremic syndrome. Within 1 year after a diagnosis of this syndrome, up to 65% of patients treated with plasma exchange or infusion sustain permanent renal damage, have progression to ESRD, or die.

Among patients with atypical hemolytic–uremic syndrome who undergo kidney transplantation, graft failure is reported in 60 to 90% of patients within 1 year. Combined liver and kidney transplantation may normalize complement regulation in patients with certain genetic defects, but it is associated with substantial morbidity and mortality, including a mortality of 14% in the short term.

Eculizumab (Soliris, Alexion Pharmaceuticals), a terminal complement inhibitor, is a humanized monoclonal antibody that binds with high affinity to the human C5 complement protein and blocks the generation of proinflammatory C5a and C5b-9. It is approved for the treatment of paroxysmal nocturnal hemoglobinuria. Previous case reports have suggested that eculizumab is effective in atypical hemolytic–uremic syndrome. In two separate 26-week, phase 2 studies with long-term extension phases, we evaluated the efficacy and safety of eculizumab in patients with atypical hemolytic–uremic syndrome and clinical evidence of progressing thrombotic microangiopathy (trial 1) and in patients with disease of long duration, chronic kidney damage, and prolonged treatment with plasma exchange or infusion (trial 2). The data from these prospective trials, as well as data from a separate retrospective study (unpublished data), were used by regulatory agencies in the United States, Europe, and other countries for the approval of eculizumab in the treatment of atypical hemolytic–uremic syndrome.

METHODS

PATIENTS

At 27 European and North American clinical sites, we enrolled patients with a diagnosis of atypical hemolytic–uremic syndrome who were 12 years of age or older and weighed 40 kg or more. Eligibility criteria differed between the studies (Fig. 1). In trial 1, patients were eligible if they had evidence of progressive thrombotic microangiopathy after four or more sessions of plasma exchange or infusion in the prior week. In trial 2, patients were eligible if they had no decrease in the platelet count of more than 25% for at least 8 weeks before they received the first dose of eculizumab and were being treated with plasma exchange or infusion at least once every 2 weeks but no more than three times per week (Fig. 1). Both studies required evidence of hemolysis (e.g., lactate dehydrogenase level at or above the upper limit of the normal range, haptoglobin level below the lower limit of the normal range, or the presence of schistocytes) and impaired renal function (creatinine level at or above the upper limit of the normal range). Identification of complement gene mutations or complement factor H autoantibodies was not required. Key exclusion criteria for both trials were ADAMTS13 (a disintegrin and metalloproteinase with a thrombospondin type 1 motif, member 13) activity at or below 5% in plasma, evidence of Shiga toxin–producing Escherichia coli infection, or prior eculizumab exposure.

STUDY DESIGN

The studies included several periods: screening (a maximum of 3 days in trial 1 and 2 weeks in trial 2), an 8-week observation period (in trial 2 only), eculizumab treatment (26 weeks and a long-term extension period), and an 8-week follow-up period if eculizumab was discontinued. Patients received the first eculizumab dose...
Clinical diagnosis of atypical HUS

**Trial 1**
- Progressing TMA measured by low platelet count (<150x10^9/liter) at screening and a decrease of >25% lower than the average of 3 platelet count measures before the most recent TMA complication
- ≥4 PE/PI sessions in the wk before screening
- Evidence of hemolysis: LDH ≥ULN, haptoglobin <LLN, or schistocytes
- Impaired renal function (creatinine ≥ULN)
- ADAMTS13 activity >5% in plasma, no STEC infection
- No requirement for an identified genetic mutation

17 Patients were screened
17 Were treated
15 Completed 26 wk
2 Did not continue into extension study
13 Continued to data-cutoff point (median duration, 64 wk)

**Trial 2**
- No platelet count decrease >25% during the 8-wk observation period
- ≥1 PE/PI sessions every 2 wk, but ≤3 times per wk for ≥8 wk
- Evidence of hemolysis: LDH ≥ULN, haptoglobin <LLN, or schistocytes
- Impaired renal function (creatinine ≥ULN)
- ADAMTS13 activity >5% in plasma, no STEC infection
- No requirement for an identified genetic mutation

23 Patients were screened
20 Were treated
20 Completed 26 wk
1 Did not continue into extension study
19 Continued to data-cutoff point (median duration, 62 wk)

**Figure 1. Screening, Treatment, and Follow-up.**

ADAMTS13 (a disintegrin and metalloproteinase with a thrombospondin type 1 motif, member 13) was measured at a central laboratory. HUS denotes hemolytic–uremic syndrome, LDH lactate dehydrogenase, LLN lower limit of the normal range, PE/PI plasma exchange or infusion, STEC Shiga toxin–producing *Escherichia coli*, TMA thrombotic microangiopathy, and ULN upper limit of the normal range.

1 to 6 hours after their most recent plasma exchange or infusion session. Eculizumab was administered intravenously at a dose of 900 mg per week for 4 weeks, a dose of 1200 mg 1 week later, and a maintenance dose of 1200 mg every 2 weeks. Patients who received plasma exchange or infusion during the eculizumab treatment period received a supplemental dose of 600 mg before plasma infusion or within 1 hour after the completion of each plasma exchange. All patients received meningococcal vaccination at least 14 days before the initiation of...
eculizumab treatment or they received prophylactic antibiotic therapy until 2 weeks after vaccination.

RESULTS

Patients

Thirty-seven patients with atypical hemolytic-uremic syndrome were enrolled in the trials (Fig. 1). For the 17 patients (16 adults and 1 adolescent) with progressive thrombotic microangiopathy who were enrolled in trial 1, the median interval between diagnosis of atypical hemolytic-uremic syndrome and screening was 9.7 months (Table 1). All patients had substantial renal damage (100% had an estimated GFR of <60 ml per minute per 1.73 m² of body-surface area for a median of 17 days). All but 1 patient (who could not undergo plasma exchange or infusion because of side effects) received plasma exchange or infusion within 1 week before initiation of treatment with eculizumab (Section 2 in the Supplementary Appendix). For the 20 patients (15 adults and 5 adolescents) enrolled in trial 2, the interval between diagnosis and screening was longer (median, 48.3 months), and most of the patients had chronic renal insufficiency (90% had an estimated GFR of <60 ml per minute per 1.73 m² for a median of 299 days) and were re-
ceiving long-term plasma exchange or infusion (median duration of treatment, 10.1 months) (Table 1).

In trial 1, patients were treated with ecu-
lizumab for 26 weeks (Fig. 1). Thirteen patients
(76%) continued to receive eculizumab during
the extension period. At the data-cutoff point, the
median duration of eculizumab treatment
was 64 weeks (range, 2 to 90). In trial 2, patients
were also treated with eculizumab for 26 weeks,
with 19 patients (95%) continuing to receive ecu-
lizumab during the extension period. At the
data-cutoff point, the median duration of treat-
ment with eculizumab was 62 weeks (range, 26
to 74). A total of 24% of patients in trial 1 and
35% of patients in trial 2 had no identified
complement gene mutation or complement fac-
tor H autoantibodies (Table 1).

PRIMARY END POINTS
In trial 1, eculizumab treatment was associated
with a significant absolute increase in the platelet
count from baseline to week 26 (mean, 73×10^9
per liter; 95% confidence interval [CI], 40×10^9
per liter to 105×10^9 per liter; P<0.001) (Table 2, and Fig. 2A)
and to week 64 (91×10^9 per liter; 95% CI, 67×10^9
per liter to 116×10^9 per liter; P<0.001) (Table 2). The
platelet count was significantly increased by
day 7 (P=0.03) (Fig. 2A). Fifty-three percent of the
patients with an abnormal platelet count at base-
line had a normal platelet count (≥150×10^9 per liter)
by day 7, and 87% had platelet counts that remained
normal at both weeks 26 and 64. All 13 patients
with a low platelet count at baseline who were
treated for 26 weeks had normalization of the
platelet count by week 26, and in all 13 patients
who entered the extension period, platelet counts
remained normal through the median treatment
duration of 64 weeks (Table 2, and Section 6 in
the Supplementary Appendix).

In trial 2, a total of 16 of 20 patients (80%)
met the primary end point by week 26; this pro-
portion increased to 85% through the median
treatment duration of 62 weeks. Four patients
did not meet the end point at 26 weeks because
of a transient decrease in the platelet count of
more than 25% from baseline, although all four
maintained normal platelet counts. With initia-
tion of eculizumab, plasma exchange or infu-
sion was discontinued in all patients, and no new
dialysis was required.

Normalization of hematologic values (the
platelet count and lactate dehydrogenase levels)
occurred in 88% of patients in trial 1 and in
90% of patients in trial 2 (Table 2). In both tri-
als, positive results were seen for all end points
in patients with or without identified genetic
mutations or complement factor H autoantibod-
ies (Section 3 in the Supplementary Appendix).

SECONDARY END POINTS
Thrombotic Microangiopathic Outcomes
In trial 1, a total of 15 of the 17 patients (88%) had
thrombotic microangiopathy event–free status
through week 26, as did 13 patients who were
treated for 64 weeks (Table 2). A total of 15 pa-
tients (88%) did not receive plasma exchange or
infusion for the entire duration of the study. One
patient received five sessions of plasma exchange
or infusion without an interruption in eculizu-
mab treatment, and 1 received plasma exchange
or infusion after discontinuation of eculizumab
and withdrawal from the study because of a pro-
tocol violation.

Renal Outcomes
After discontinuation of plasma exchange or in-
fusion and initiation of eculizumab treatment,
there were continuous, time-dependent increases
in the estimated GFR from baseline to week 26
(mean increase in trial 1, 32 ml per minute per
1.73 m^2; 95% CI, 14 to 49; P=0.001; mean in-
crease in trial 2, 6 ml per minute per 1.73 m^2;
95% CI, 3 to 9; P<0.001). This improvement was
maintained at week 60 (mean increase in trial 1,
32 ml per minute per 1.73 m^2; 95% CI, 16 to 47;
P<0.001; mean increase in trial 2, 9 ml per minute
per 1.73 m^2; 95% CI, 4 to 14; P=0.003) (Fig.
2B and 2C). In both trials, improvement in the
estimated GFR was accompanied by a decrease in
proteinuria in patients with baseline proteinuria
of grade 1+ or higher (P<0.001 in trial 1 and
P=0.03 in trial 2 at 1 year) (Table 1). In addition,
in trial 1, dialysis was discontinued in four of
five patients (80%) who had required dialysis at
the time of initiation of eculizumab, and these
patients remained dialysis-free throughout eculiz-
umab treatment. In both trials, earlier initiation
of eculizumab (i.e., a shorter interval between
the current clinical manifestation of atypical he-
molytic–uremic syndrome and enrollment) was
associated with a significantly greater improve-
ment in the estimated GFR throughout the treat-
ment period (P=0.007 in trial 1 and P<0.001 in
A 3-piece linear model showed that the change in the estimated GFR before eculizumab treatment (slope 1) did not differ significantly from zero in either trial. From the initiative to treat population, Table 1 demonstrates the baseline demographic and clinical characteristics.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Trial 1 (N=17)</th>
<th>Trial 2 (N=20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age — yr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Range</td>
<td>17–68</td>
<td>13–63</td>
</tr>
<tr>
<td>Female sex — no. (%)</td>
<td>12 (71)</td>
<td>12 (60)</td>
</tr>
<tr>
<td>White race — no.†</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>Time from diagnosis of atypical HUS to screening — mo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median</td>
<td>9.7</td>
<td>48.3</td>
</tr>
<tr>
<td>Range</td>
<td>0.3–235.9</td>
<td>0.7–285.8</td>
</tr>
<tr>
<td>Time from current clinical presentation of atypical HUS to screening — mo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median</td>
<td>0.8</td>
<td>8.6</td>
</tr>
<tr>
<td>Range</td>
<td>0.2–3.7</td>
<td>1.2–45.0</td>
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<tr>
<td>First clinical manifestation of atypical HUS — no. (%)</td>
<td>7 (41)</td>
<td>5 (25)</td>
</tr>
<tr>
<td>History of kidney transplantation — no. (%)</td>
<td>7 (41)</td>
<td>8 (40)</td>
</tr>
<tr>
<td>Dialysis before the first dose of eculizumab — no. (%)</td>
<td>6 (35)‡</td>
<td>2 (10)§</td>
</tr>
<tr>
<td>Sessions of plasma exchange or infusion during current clinical presentation — no./patient</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median</td>
<td>17</td>
<td>62</td>
</tr>
<tr>
<td>Range</td>
<td>2–35¶</td>
<td>20–230</td>
</tr>
<tr>
<td>Duration of plasma exchange or infusion treatment — mo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median</td>
<td>0.7</td>
<td>10.1</td>
</tr>
<tr>
<td>Range</td>
<td>0.1–3.2</td>
<td>2.4–47.0</td>
</tr>
<tr>
<td>No identified genetic mutation or autoantibody — no. (%)</td>
<td>4 (24)</td>
<td>6 (30)</td>
</tr>
<tr>
<td>Identified genetic mutation, autoantibody, or both — no. (%)</td>
<td>13 (76)</td>
<td>14 (70)</td>
</tr>
<tr>
<td>Single</td>
<td>9 (53)</td>
<td>8 (40)</td>
</tr>
<tr>
<td>Multiple</td>
<td>4 (24)</td>
<td>6 (30)</td>
</tr>
<tr>
<td>Platelet count</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median — x10^9/liter</td>
<td>118</td>
<td>218</td>
</tr>
<tr>
<td>Range — x10^9/liter</td>
<td>62–161</td>
<td>105–421</td>
</tr>
<tr>
<td>&lt;150x10^9/liter — no. (%)</td>
<td>15 (88)**</td>
<td>3 (15)</td>
</tr>
<tr>
<td>Hemoglobin — g/liter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median</td>
<td>87</td>
<td>108</td>
</tr>
<tr>
<td>Range</td>
<td>67–126</td>
<td>79–131</td>
</tr>
<tr>
<td>Lactate dehydrogenase</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median — U/liter</td>
<td>269</td>
<td>200</td>
</tr>
<tr>
<td>Range — U/liter</td>
<td>134–634</td>
<td>151–391</td>
</tr>
<tr>
<td>&gt;Upper limit of normal range — no. (%)</td>
<td>10 (59)</td>
<td>4 (20)</td>
</tr>
<tr>
<td>Serum creatinine — μmol/liter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median</td>
<td>256</td>
<td>234</td>
</tr>
<tr>
<td>Range</td>
<td>124–787</td>
<td>106–893</td>
</tr>
</tbody>
</table>
tion of eculizumab treatment through day 28 (slope 2), there was a rapid and significant increase in the estimated GFR in both trials (P<0.001 in trial 1 and P=0.001 in trial 2). The slope of change in the estimated GFR from day 0 to 28 was significantly greater than the slope of change during the pretreatment period (slope 2 vs. slope 1; P<0.001 in trial 1 and P=0.007 in trial 2). In trial 1, the improvements in the estimated GFR from day 0 to 28 were maintained from day 29 through the data-cutoff point (slope 3), with no further increase, whereas in trial 2, the estimated GFR continued to improve after day 28 (P=0.03) (Fig. S3 and S4 in the Supplementary Appendix).

Health-Related Quality of Life Outcomes

Eculizumab was associated with a significant improvement in health-related quality of life. The EQ-5D scores range from 0 to 1, with higher scores

<table>
<thead>
<tr>
<th>Variable</th>
<th>Trial 1 (N = 17)</th>
<th>Trial 2 (N = 20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated GFR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median — ml/min/1.73 m²</td>
<td>19</td>
<td>28</td>
</tr>
<tr>
<td>Range — ml/min/1.73 m²</td>
<td>5–59</td>
<td>6–72</td>
</tr>
<tr>
<td>≥60 ml/min/1.73 m² — no. (%)</td>
<td>0††</td>
<td>2 (10)‡‡</td>
</tr>
<tr>
<td>45–59 ml/min/1.73 m² — no. (%)</td>
<td>1 (6)</td>
<td>2 (10)</td>
</tr>
<tr>
<td>30–44 ml/min/1.73 m² — no. (%)</td>
<td>4 (24)</td>
<td>6 (30)</td>
</tr>
<tr>
<td>15–29 ml/min/1.73 m² — no. (%)</td>
<td>5 (29)</td>
<td>6 (30)</td>
</tr>
<tr>
<td>&lt;15 ml/min/1.73 m² or receiving dialysis — no. (%)</td>
<td>7 (41)</td>
<td>4 (20)</td>
</tr>
<tr>
<td>Proteinuria grade ≥1+ — no. (%)§§</td>
<td>15 (88)</td>
<td>11 (55)</td>
</tr>
<tr>
<td>Urinary protein:creatinine¶¶</td>
<td>4.3±0.32</td>
<td>0.9±0.26</td>
</tr>
<tr>
<td>Medication — no. (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ESAs</td>
<td>10 (59)</td>
<td>16 (80)</td>
</tr>
<tr>
<td>ACE inhibitors or ARBs</td>
<td>6 (35)</td>
<td>18 (90)</td>
</tr>
</tbody>
</table>

* Plus–minus values are means ±SE. ACE denotes angiotensin-converting enzyme, ARB angiotensin II–receptor blocker, ESA erythropoiesis-stimulating agent, GFR glomerular filtration rate, and HUS hemolytic–uremic syndrome.
† Race was self-reported.
‡ One of the six patients who had been receiving dialysis within 8 weeks before eculizumab treatment discontinued dialysis 5 weeks before the first dose of eculizumab. The duration of dialysis before the initiation of eculizumab treatment ranged from 6 to 26 days.
§ The duration of dialysis before the initiation of eculizumab treatment was 119 days in one patient and 1128 days in the other.
¶ One patient had no plasma exchange or infusion sessions during the 7 days before the initiation of eculizumab treatment and did not meet the inclusion criterion of a minimum of four sessions of plasma exchange or infusion before screening because this patient had an allergic reaction and discontinued plasma exchange or infusion after two sessions. (See Section 2 in the Supplementary Appendix for additional information.)
‖ One patient in trial 2 who had an isolated complement factor H–related 3/1 deletion (a risk factor for atypical hemolytic–uremic syndrome) was included under “no identified genetic mutation” in this analysis.
** Two patients with baseline median platelet counts of 150×10⁹/liter or higher were eligible for inclusion, since their average platelet count during screening was lower than 150×10⁹/liter.
†† The median duration of an estimated GFR of less than 60 ml per minute per 1.73 m² in all patients was 17 days (range, 5 to 105).
‡‡ The median duration of an estimated GFR of less than 60 ml per minute per 1.73 m² in 18 patients was 299 days (range, 91 to 553). Of the two patients with an estimated GFR between 60 and 89 ml per minute per 1.73 m² at baseline, one patient had an estimated GFR of less than 60 ml per minute per 1.73 m² for 118 days and an estimated GFR of 60 to 90 ml per minute per 1.73 m² for 556 days, and the other patient had an estimated GFR of less than 60 ml per minute per 1.73 m² for 42 days and an estimated GFR of 60 to 89 ml per minute per 1.73 m² for 329 days.
§§ Proteinuria was reported according to grade (negative, traces, 1+, 2+, etc.) or as urinary protein with a normal range of 0 to 12 mg per deciliter.
¶¶ Protein was measured in grams per liter, and creatinine was measured in millimoles per liter.
indicating a better quality of life. In trial 1, the mean increase in the EQ-5D score at week 26 was 0.32 (95% CI, 0.24 to 0.39; P<0.001) (Section 6 and Fig. S5 in the Supplementary Appendix), and in trial 2, the mean increase was 0.10 (95% CI, 0.05 to 0.15; P<0.001) (Table 2, and Section 6 and Fig. S6 in the Supplementary Appendix). The clinically meaningful threshold of 0.06 was exceeded in 87% of

<table>
<thead>
<tr>
<th>Table 2. Primary and Secondary End Points.†</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>End Point</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Efficacy</strong></td>
</tr>
<tr>
<td>Change in platelet count from baseline — ×10^9/liter</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>95% CI</td>
</tr>
<tr>
<td>P value for comparison with 0</td>
</tr>
<tr>
<td>Normalization of platelet count — no./total no. (%)</td>
</tr>
<tr>
<td>All patients</td>
</tr>
<tr>
<td>Patients with baseline count of &lt;150×10^9/liter</td>
</tr>
<tr>
<td>Thrombotic microangiopathy event–free status — no./total no. (%)</td>
</tr>
<tr>
<td>Normalization of hematologic values — no./total no. (%)</td>
</tr>
<tr>
<td><strong>Thrombotic microangiopathy</strong></td>
</tr>
<tr>
<td>Intervention rate — no. of events (plasma exchange or infusion, dialysis, or both)/patient/day</td>
</tr>
<tr>
<td>Before eculizumab treatment</td>
</tr>
<tr>
<td>Median</td>
</tr>
<tr>
<td>Range</td>
</tr>
<tr>
<td>During eculizumab treatment</td>
</tr>
<tr>
<td>Median</td>
</tr>
<tr>
<td>Range</td>
</tr>
<tr>
<td>P value for comparison with pretreatment values</td>
</tr>
<tr>
<td>Complete thrombotic microangiopathic response — no./total no. (%)</td>
</tr>
<tr>
<td>Increase in hemoglobin of &gt;20 g/liter — no./total no. (%)</td>
</tr>
<tr>
<td>Lactate dehydrogenase supper limit of normal range — no./total no. (%)</td>
</tr>
<tr>
<td><strong>Renal function</strong></td>
</tr>
<tr>
<td>Decrease in serum creatinine level of ≥25% — no./total no. (%)</td>
</tr>
<tr>
<td>Increase in estimated GFR of ≥15 ml/min/1.73 m² — no./total no. (%)</td>
</tr>
<tr>
<td>Improvement in CKD of at least 1 stage — no./total no. (%)</td>
</tr>
<tr>
<td>Decrease in proteinuria by ≥1 grade in patients with proteinuria grade ≥1 at baseline — no./total no.</td>
</tr>
<tr>
<td>Decrease in urinary protein:creatinine‖</td>
</tr>
<tr>
<td>P value for comparison with baseline</td>
</tr>
</tbody>
</table>

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In both trials, eculizumab significantly reduced complement activity within 1 hour after initiation of treatment, and all patients had complete inhibition of complement activity, which was maintained through week 26 (P<0.001) (Fig. 2D). The specified dosing schedule was sufficient to achieve and maintain the minimum serum concentration of eculizumab required to block terminal complement activation (Section 8 in the Supplementary Appendix).

Safety

Adverse events are listed in Table 3 and Section 9 in the Supplementary Appendix. There were no cases of meningococcal infection or infection-related serious adverse events. All patients were alive at the time of data cutoff. In trial 1, all patients had at least one serious adverse event; four events were reported as being possibly related to eculizumab, one of which was considered severe (hypertension in a patient with a history of this disorder). In trial 2, a total of 10 patients (50%) had serious adverse events, of whom 2 patients had a total of three serious adverse events that were possibly or probably drug-related (peritonitis, influenza, and vein disorder). One patient had one drug-related serious adverse event and the other patient had two such events. All serious adverse events possibly or probably related to eculizumab resolved without interruption of treatment. No new adverse events were reported after the first 26 weeks of treatment. Adverse events were similar among patient subgroups, in-
was associated with large and sustained improvements in renal function, and four of five patients who were receiving dialysis at the beginning of the study no longer required it (trial 1). These results showed that treatment with a terminal complement inhibitor improved renal function across patient subgroups, including those with long-standing, substantial kidney damage who had undergone plasma exchange or infusion.

Earlier intervention with eculizumab (i.e., a shorter interval between the current clinical manifestation of atypical hemolytic–uremic syndrome and initiation of treatment) was associated with significantly greater improvement in the estimated GFR in both trials. These findings suggest that starting eculizumab treatment earlier may lead to improved clinical outcomes and reversal of organ damage. Eculizumab was also associated with significant improvements in health-related quality of life.

Historically, the risk of ESRD or death has been similar among patients with and those without identified complement mutations or complement factor H autoantibodies.8 In the present trials, the response to eculizumab therapy was also similar, irrespective of status with respect to these two factors,8 although the studies were not powered to evaluate differences according to mutation status. This finding lends support to the recommendation that treatment with eculizumab in patients with atypical hemolytic–uremic syndrome be considered without requiring results of complement mutation testing.24

Treatment with eculizumab during a period of 62 to 64 weeks was not associated with major adverse events in these studies. The safety profile of eculizumab reported here, for patients with atypical hemolytic–uremic syndrome, was generally consistent with that in a study involving patients with paroxysmal nocturnal hemoglobinuria who received treatment for up to 8 years.28 Infection-related serious adverse events were not observed in our trials. Rates of adverse events remained steady or declined between the initial 26-week period and the extension period. No new adverse events emerged after the initial 26-week study period. Adverse events were similar among patient subgroups, including patients who had undergone kidney transplantation and were receiving concomitant immunosuppressive therapy. No deaths were reported in either trial. Follow-up of patients is ongoing.

Deviations from approved eculizumab dosing...
are associated with a risk of clinical complications, including rapid progression to ESRD.\textsuperscript{14,34,35} Such approaches include limiting eculizumab treatment to a single dose, early discontinuation followed by reinitiation of treatment, and administration of doses at intervals longer than those recommended in the eculizumab prescribing information.\textsuperscript{24,30} Five of 18 patients who missed eculizumab doses in our two prospective trials or a retrospective study had severe subsequent complications of thrombotic microangiopathy.\textsuperscript{29,30} These findings highlight the likelihood of ongoing thrombotic microangiopathy in patients with atypical hemolytic–uremic syndrome and underscore the importance of continued monitoring of patients and sustained treatment.\textsuperscript{24,30}

Previous studies have suggested that eculizumab is effective in treating atypical hemolytic–uremic syndrome.\textsuperscript{20-24,34,35} To confirm an eculizumab treatment effect in these open-label, single-group trials, pretreatment data were used as within-patient controls. In both trials, the rate of intervention for thrombotic microangiopathy was significantly lower during the period of eculizumab treatment than during the period before treatment. The data highlight the inadequate efficacy of management with plasma exchange or infusion and confirm the clinically relevant treatment effect of eculizumab on thrombotic microangiopathy and organ outcomes. The results of eculizumab therapy appear to represent a substantial advancement in the treatment of patients who have this severe and life-threatening systemic disease.

These two clinical studies suggest that long-term eculizumab treatment is effective in patients with atypical hemolytic–uremic syndrome, with earlier intervention associated with a greater clinical benefit. The data indicate that terminal complement inhibition with eculizumab inhibits complement-mediated thrombotic microangiopathy, decreases the need for thrombotic microangiopathy–related intervention, significantly improves the platelet count and renal function across patient groups, and is associated with substantial kidney recovery and improved clinical outcomes in patients with atypical hemolytic–uremic syndrome.

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**APPENDIX**

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**Table 3.** Serious Adverse Events Considered Possibly, Probably, or Definitely Associated with Eculizumab as Identified by the Investigator (throughout the Median Treatment Duration of 64 Weeks in Trial 1 and 62 Weeks in Trial 2).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Trial 1 (N = 17)</th>
<th>Trial 2 (N = 20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patients with at least one related serious adverse event</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td>4 (24)</td>
<td>2 (10)</td>
</tr>
<tr>
<td>To wk 26</td>
<td>2 (12)</td>
<td>2 (10)</td>
</tr>
<tr>
<td>Wk 26 to data-cutoff point</td>
<td>2 (12)</td>
<td>1 (5)</td>
</tr>
<tr>
<td>Serious adverse events</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accelerated hypertension</td>
<td>2 (12); moderate severity</td>
<td></td>
</tr>
<tr>
<td>Hypertension</td>
<td>1 (6); severe</td>
<td></td>
</tr>
<tr>
<td>Influenza</td>
<td>1 (5); severe</td>
<td></td>
</tr>
<tr>
<td>Peritonitis</td>
<td>1 (5); severe</td>
<td></td>
</tr>
<tr>
<td>Venous sclerosis at infusion site</td>
<td>1 (5); severe</td>
<td></td>
</tr>
<tr>
<td>Asymptomatic bacteriuria</td>
<td>1 (6); mild</td>
<td></td>
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</tbody>
</table>
References