Effect of the complement inhibitor eculizumab on thromboembolism in patients with paroxysmal nocturnal hemoglobinuria

Peter Hillmen,[1] Petra Muus,[2] Ulrich Dührsen,[3] Antonio M. Risitano,[4] Jörg Schubert,[5] Lucio Luzzatto,[6] Hubert Schrezenmeier,[7] Jeffrey Szer,[8] Robert A. Brodsky,[9] Anita Hill,[1] Gerard Socié,[10] Monica Bessler,[11] Scott A. Rollins,[12] Leonard Bell,[12] Russell P. Rother,[12] and Neal S. Young[13]

[1]Leeds General Infirmary, Leeds, United Kingdom; [2]Radboud University Medical Center, Nijmegen, The Netherlands; [3]University Essen, Essen, Germany; [4]Federico II University, Naples, Italy; [5]Saarland University Medical School, Homburg-Saarland, Germany; [6]Istituto Toscano Tumori, Florence, Italy; [7]Institute of Transfusion Medicine, University Hospital, Ulm, Germany; [8]Royal Melbourne Hospital, Melbourne, Australia; [9]Johns Hopkins School of Medicine, Baltimore, MD; [10]Hôpital Saint-Louis and Institut National de la Santé et de la Recherche Médicale (INSERM), Paris, France; [11]Washington University, St Louis, MO; [12]Alexion Pharmaceuticals, Cheshire, CT; and [13]National Heart, Lung, and Blood Institute, Bethesda, MD

Hemolysis and hemoglobinemia contribute to serious clinical sequelae in hemolytic disorders. In paroxysmal nocturnal hemoglobinuria (PNH) patients, hemolysis can contribute to thromboembolism (TE), the most feared complication in PNH, and the leading cause of disease-related deaths. We evaluated whether long-term treatment with the complement inhibitor eculizumab reduces the rate of TE in patients with PNH. Clinical trial participants included all patients in the 3 eculizumab PNH clinical studies, which recruited patients between 2002 and 2005 (n = 195); patients from these studies continued treatment in the current multinational open-label extension study. Thromboembolism rate with eculizumab treatment was compared with the pretreatment rate in the same patients. The TE event rate with eculizumab treatment was 1.07 events/100 patient-years compared with 7.37 events/100 patient-years ($P < .001$) prior to eculizumab treatment (relative reduction, 85%; absolute reduction, 6.3 TE events/100 patient-years). With equalization of the duration of exposure before and during treatment for each patient, TE events were reduced from 39 events before eculizumab to 3 events during eculizumab ($P < .001$). The TE event rate in antithrombotic-treated patients (n = 103) was reduced from 10.61 to 0.62 events/100 patient-years with eculizumab treatment ($P < .001$). These results show that eculizumab treatment reduces the risk of clinical thromboembolism in patients with PNH. This study is registered at http://clinicaltrials.gov (study ID no. NCT00122317). (Blood. 2007;110: 4123-4128)

Introduction

Intravascular hemolysis and cell-free plasma hemoglobin have been implicated in the serious clinical sequelae of various hemolytic disorders.[1] Hemolysis is the primary clinical manifestation of the uncommon disease paroxysmal nocturnal hemoglobinuria (PNH) and has been shown to result in chronic disabling morbidities including anemia, severe fatigue, difficulty in functioning, pain, and thrombosis, all of which have a major effect on the patient's quality of life.[1-5] Paroxysmal nocturnal hemoglobinuria is defined by the acquired genetic deficiency of glycosylphosphatidylinositol (GPI)–linked proteins from the surface of blood cells. The absence of GPI-linked complement regulatory proteins on PNH erythrocytes renders them susceptible to terminal complement-mediated hemolysis.

Hemolysis most likely contributes to thromboembolism (TE) in PNH, as patients with larger PNH clones have a higher incidence of TE and events have been temporally associated with increased hemolysis.[6-10] Although the mechanism is not fully understood, hemolysis has been implicated in the initiation of platelet activation and aggregation.[1] Additional in vitro studies have suggested that complement may directly activate platelets from PNH patients.[11,12]

Thromboembolism is the leading cause of mortality in patients with PNH,[2,3,13-17] and an initial thrombotic event increases the relative risk of death in PNH 5- to 10-fold.[15,17] Retrospective studies suggest that, in non-Asian patients, TE accounts for approximately 40% to 67% of deaths with known causes.[13-17] Further, 29% to 44% of patients with PNH have been reported to suffer from at least one TE event in the course of their disease.[13-16]

In a retrospective study of 67 high-risk patients with PNH not taking prophylactic anticoagulants, the TE rate was estimated at 3.7 events per 100 patient-years (19 TE events in 511.5 patient-years), while 0 TE events in 117.8 patient-years was observed in a heterogeneous group of 39 patients with PNH treated with anticoagulants as primary prophylaxis.[8] However, in other reports, new TE events as well as progression of existing TE have been observed in patients with PNH, despite the use of anticoagulants and/or antiplatelet agents.[7,14] The risk for fatal hemorrhage in patients with PNH is significant, in part due to the frequent occurrence of thrombocytopenia.[8,14]

Eculizumab (Soliris) is a humanized monoclonal antibody that targets complement protein C5, thereby preventing assembly of the

Submitted June 13, 2007; accepted August 9, 2007. Prepublished online as *Blood* First Edition paper, August 16, 2007; DOI 10.1182/blood-2007-06-095646.

An Inside *Blood* analysis of this article appears at the front of this issue.

The online version of this article contains a data supplement.

The publication costs of this article were defrayed in part by page charge payment. Therefore, and solely to indicate this fact, this article is hereby marked "advertisement" in accordance with 18 USC section 1734.

terminal complement complex (also called the membrane attack complex or MAC) during complement activation. In clinical studies to date, eculizumab treatment reduced hemolysis and improved anemia, fatigue, and quality of life in patients with PNH.[18,19] In this report, we evaluate the effect of long-term treatment with eculizumab on the prespecified clinical outcome of TE on an intention-to-treat basis in a multinational phase 3 open-label extension study that enrolled patients from 3 independent eculizumab PNH clinical studies (n = 195). We explore the robustness of the effect of eculizumab treatment on TE in subgroup analyses.

Patients and methods

Study design and patients

The number of TE events and the incidence rates were determined in patients from 3 independent parent clinical studies (the phase 2 pilot study and its extensions,[19] the phase 3 TRIUMPH study,[18] and the phase 3 SHEPHERD study[20]) and the common phase 3 extension study. All of the protocols were approved by the institutional review board at each center, and informed consent was obtained in accordance with the Declaration of Helsinki from all patients.

The open-label 12-week phase 2 pilot study was conducted in 11 patients at 2 study centers in the United Kingdom.[19] Patients who completed the pilot study were eligible to enroll in a one-year extension study followed by a 2-year extension study. Patients 18 years or older who had received at least 4 red cell transfusions in the previous 12 months and had a PNH type III erythrocyte population of at least 10% were eligible to enroll in the pilot study. Patients who were taking stable doses of immunosuppressive drugs (eg, cyclosporin), warfarin, and iron supplements were permitted to continue them during the study. Eculizumab was dosed at 600 mg via intravenous infusion every 7 days for 4 doses, 900 mg 7 days later, and 900 mg every 14 days as a maintenance dose.

The double-blind placebo-controlled 26-week phase 3 efficacy and safety study (TRIUMPH) was conducted in 87 patients in the United States, Europe, Australia, and Canada.[18] Patients 18 years or older, with at least 4 red cell transfusions in the previous 12 months, a PNH type III erythrocyte population of at least 10% or higher, platelet count of at least 100×10^9/L or higher, and lactate dehydrogenase (LDH) level of 1.5 times or more of the upper limit of normal were eligible to enroll. Exclusion criteria were previously described.[18] Patients who were taking stable doses of immunosuppressive drugs, anticoagulants, and iron supplements were permitted to continue them during the study. Patients were centrally randomized (1:1) and stratified according to red cell units transfused in the past year to receive either placebo or eculizumab. Study medication was dosed as follows: eculizumab (600 mg) or placebo via intravenous infusion every 7 ($\pm$ 2) days for 4 doses; eculizumab (900 mg) or placebo via intravenous infusion 7 ($\pm$ 2) days later; followed by a maintenance dose of eculizumab (900 mg) or placebo via intravenous infusion every 14 ($\pm$ 2) days, for a total of 26 weeks of treatment.

The open-label 52-week phase 3 study (SHEPHERD) was conducted in 97 patients in the United States, Europe, Australia, and Canada. Patient characteristics were similar to those of patients treated in TRIUMPH except that the pretreatment transfusion eligibility was adjusted to one or more red cell transfusions in the previous 24 months and the minimum platelet count requirement was lowered to 30×10^9/L; all patients received the identical eculizumab dose as in the TRIUMPH study.

The common open-label 102-week phase 3 extension study is an ongoing study in which a total of 187 patients have enrolled following completion of the parent clinical studies (195 patients were enrolled in parent studies). Placebo-treated TRIUMPH patients entering the phase 3 extension study received the same eculizumab regimen outlined for the TRIUMPH and SHEPHERD studies. Eculizumab-treated patients from the pilot, TRIUMPH, or SHEPHERD studies that entered the phase 3 extension study continued to receive the 900-mg maintenance dose of eculizumab. Doses of immunosuppressive drugs, anticoagulants, and iron supplements could be altered at the discretion of the treating physician.

Outcome measures

For patients enrolling in the TRIUMPH, SHEPHERD, and common phase 3 extension studies, each of the respective protocols specified that all adverse events and past medical histories were to be evaluated by the principal investigator to identify clinical TE events as defined by the same major adverse vascular event (MAVE) criteria in all studies. For each study, the protocol specified that the principal investigator record the description, location, method of diagnosis, date of diagnosis, and date resolved for each thrombosis/MAVE event in preidentified case report form fields for events both prior to and during eculizumab treatment. Because of the diverse anatomic locations of thromboses in patients with PNH, multiple diagnostic tests were used. At least 73% (91/124) of pretreatment MAVEs were objectively identified, and the most frequent tests were ultrasound, computed tomography (CT) scan, magnetic resonance imaging (MRI), and angiogram. Events classified as MAVE included thrombophlebitis/deep vein thrombosis, pulmonary embolus, cerebrovascular accident, amputation, myocardial infarction, transient ischemic attack, unstable angina, renal vein thrombosis, mesenteric vein thrombosis, portal vein thrombosis, gangrene, acute peripheral vascular occlusion, sudden death, and a category for other events. All adverse and past medical history events for patients enrolling in the pilot study were also evaluated in the same manner, and the MAVE criteria were retrospectively applied. All MAVEs were independently source verified. The intention-to-treat analysis was based on all 195 patients who enrolled in all 3 parent clinical studies. The pretreatment patient-years included the period extending from the earlier of the date of the diagnosis of PNH or the first thrombotic event to first eculizumab treatment. Pre-eculizumab treatment TE events included all events in all patients prior to enrollment in each of the studies (and during placebo treatment in TRIUMPH). The eculizumab treatment TE events included all events during the period commencing from the first eculizumab dose in the parent studies until the earlier of the follow-up after the last dose of eculizumab in the parent or extension studies or the database lock in November 2006. For the determination of TE events in patients receiving chronic antithrombotic agents, the Anatomical Therapeutic Chemical Classification System was used to identify relevant chronic therapies including anticoagulant and antiplatelet agents.[21]

Statistical analysis

For each type of TE event and for the total group of events collected in the thrombosis record case report form, the incidence rate was tabulated. Rate of thrombosis per patient year for the pre-eculizumab and the eculizumab treatment periods was analyzed for the overall patient population and for each parent clinical study.

TE event rates for pre-eculizumab and eculizumab treatment periods were calculated as the total number of TE events divided by the time in years on a per patient basis. Wilcoxon signed-rank test was used for the prespecified analysis on an intention-to-treat basis and for all subanalyses of the differences between the pre-eculizumab and eculizumab treatment TE events and incidence rates.

Results

Study population and baseline characteristics

The prespecified TE clinical outcome was determined on an intention-to-treat basis in the multinational phase 3 open-label extension study that enrolled patients from 3 independent eculizumab PNH clinical studies (n = 195). Baseline characteristics of patients in each of the parent clinical studies are shown in Table 1. Ninety-six percent of all eligible patients chose to enroll into the common extension study.

Clinical outcomes

Hemolysis is the primary clinical manifestation of PNH and is associated with serious morbidities in PNH including TE.[1,6-9] Inhibition of terminal complement with eculizumab rapidly and

Table 1. Baseline characteristics of patients with PNH from parent trials

Characteristics	Pilot, n = 11	TRIUMPH, n = 87*	SHEPHERD, n = 97
Sex, no. (%)			
Male	6 (55)	35 (40)	48 (49)
Female	5 (45)	52 (60)	49 (51)
Median age, y (range)	48 (21-67)	38 (18-85)	41 (18-78)
Median disease duration, y (range)	8.7 (1.7-37.9)	6.5 (0.5-38.5)	4.9 (0.1-31.4)
Reticulocyte count, $\times 10^{12}$/L (range)	0.14 (0.07-0.37)	0.21 (0.04-0.57)	0.14 (0.04-0.76)
Platelet count, $\times 10^{9}$/L (range)	182 (36-466)	162 (59-547)	136 (23-355)
Median PNH granulocyte population size, % (range)	97.0 (47.8-99.8)	95.3 (82.6-99.5)†	96.0 (1.1-99.9)‡
Median PNH type III red cell population size, % (range)	37.0 (10.4-79.6)	29.5 (2.4-88.0)	33.5 (7.7-98.8)
History of aplastic anemia or myelodysplastic syndromes, no. (%)	8 (73)	20 (23)	31 (32)
History of TE events, no. (%)	3 (27)	17 (19)	42 (43)
Use of antithrombotic agents, no. (%)	6 (55)	44 (51)	59 (61)
Use of steroids, no. (%)	0 (0)	28 (32)	36 (37)

*Includes 43 eculizumab-treated patients and 44 placebo-treated patients.
†Based on 31 patients with baseline values.
‡Based on 94 patients with baseline values

consistently reduced hemolysis to near normal levels in patients from all parent clinical studies, while placebo treatment in the TRIUMPH study showed no effect (Figure 1). Subsequent eculizumab treatment of placebo-treated patients also resulted in a rapid and sustained reduction in hemolysis.

Prior to receiving eculizumab, application of the specified MAVE criteria to the evaluation of medical history events identified 124 TE events in the 195 study patients. Pretreatment TE events in the study group occurred in both venous (85%) and arterial (15%) sites (Table 2). The most common sites of venous thrombosis were lower extremity deep veins (18.5%), mesenteric/splenic veins (18.5%), and hepatic/portal veins (16.9%), while the most common site of arterial thrombosis was cerebrovascular accident/transient ischemic attack (13.7%).

Main outcome measure. To determine the effect of treatment with eculizumab on the incidence of TE events in PNH, the TE event rates in patients with and without eculizumab treatment were compared. Eculizumab treatment resulted in a reduction in the TE event rate in each of the individual clinical studies (Table 3). The prespecified overall TE event rate was reduced from 7.37 events per 100 patient-years (124 total events) before eculizumab treatment to 1.07 events per 100 patient-years (3 total events) with eculizumab treatment in the same patients ($P < .001$). This represented a relative reduction of 85% and an absolute reduction of 6.3 TE events per 100 patient-years. The TE event rate in placebo-treated patients from the double-blind placebo-controlled TRIUMPH study increased from 2.34 events per 100 patient-years before entering the study to 4.38 events per 100 patient-years during the 6-month period of placebo treatment.

To eliminate a potential bias arising from an unexpected change in the number of TE events immediately preceding trial entry and to adjust for the difference between the number of patient-years accumulated in the pre-eculizumab versus the eculizumab treatment periods, the duration of exposure before and during treatment was equalized for each patient. Compared with the number of TE events before treatment, eculizumab treatment resulted in a significant reduction in the overall number of TE events from 39 to 3 ($P < .001$; Table 4). This represented a relative reduction of 92%. To determine the pre-eculizumab TE event rate immediately preceding eculizumab treatment, the period 12 months before treatment was examined; the TE event rate during this period in the overall patient population was 17.21 TE events per 100 patient-years (191.8 total patient-years), indicating an increase in rate nearer to initiation of the eculizumab studies.

Patients receiving antithrombotics. To evaluate the potential impact of antithrombotic therapy on TE event rates with and without eculizumab treatment, the TE event rate in patients treated with antithrombotic agents was examined. Compared with the pre-eculizumab TE event rate in antithrombotic-treated patients, eculizumab treatment resulted in a reduction in the TE event rate in each of the individual clinical studies and a significant reduction in the overall TE event rate (Table 5). The TE event rate in patients receiving antithrombotics was 10.61 events per 100 patient-years before eculizumab and was reduced to 0.62 events per 100 patient-years in the same patients during eculizumab treatment ($P < .001$). This represented a relative reduction of 94% and an absolute reduction of 9.99 TE events per 100 patient-years. When the analysis of thromboses in patients receiving antithrombotics

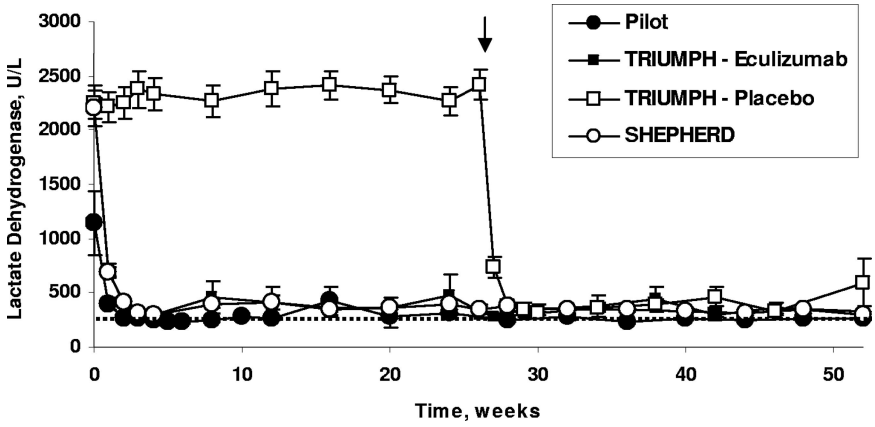

Figure 1. Levels of lactate dehydrogenase during treatment with eculizumab. Mean levels of lactate dehydrogenase reflect the degree of hemolysis in each of the parent clinical studies from baseline to week 52. The dashed line indicates the upper limit of the normal range for lactate dehydrogenase (normal range, 103 to 223 U per liter). Values from the pilot study were normalized to that of the TRIUMPH and SHEPHERD studies and include data from the subsequent one-year extension study. In eculizumab-treated patients, the mean level of lactate dehydrogenase was rapidly reduced to just above the upper limit of the normal range. In the placebo group, the mean level of lactate dehydrogenase remained highly elevated. The arrow depicts the transition of placebo-treated patients in TRIUMPH to eculizumab treatment in the phase 3 extension study at which time levels of lactate dehydrogenase rapidly reduced to near normal values.

Table 2. Sites of pretreatment thromboembolism events

TE sites	Events, no.	Percentage of total
Venous thrombosis		
Deep vein thrombosis	41	33.1
Lower extremity	23	18.5
Other*	18	14.5
Mesenteric/splenic vein thrombosis	23	18.5
Hepatic/portal vein thrombosis	21	16.9
Pulmonary embolus	8	6.5
Cerebral/internal jugular thrombosis	7	5.6
Superficial vein thrombosis	5	4.0
Arterial thrombosis		
Cerebrovascular accident/transient ischemic attack	17	13.7
Myocardial infarction/unstable angina	2	1.6
Total	124†	100

Pretreatment period includes placebo-treated patients in the TRIUMPH study.

*Includes inferior vena cava, bilateral lower extremity, pelvic, ureter, axillary, subclavian, and brachiocephalic veins.

†Occurred in 63 patients: 1 event in 35 patients, 2 events in 15 patients, 3 events in 7 patients, and 5 or more events in 6 patients.

was restricted to patients on anticoagulants (n = 91; excludes patients on antiplatelet agents), the TE event rate was reduced from 11.54 events per 100 patient-years before eculizumab to 0.72 events per 100 patient-years during eculizumab treatment ($P < .001$).

Discussion

Intravascular hemolysis and the release of red blood cell hemoglobin have been linked to the occurrence of thrombosis and other serious morbidities in various hemolytic disorders.[1] Thromboembolism is a serious and life-threatening complication in PNH and the single most frequent cause of death in patients. Prospective analysis of patient data pooled from 3 clinical studies and a common extension study enabled us to carry out a comparison of the TE event rate in nontreated and in eculizumab-treated patients with PNH. This analysis demonstrates that eculizumab treatment resulted in a dramatic reduction in the TE event rate from 7.37 to 1.07 TE events per 100 patient-years. The reduction in the number of TE events and the TE incidence rates with eculizumab were robust and were not diminished in several clinically relevant sensitivity analyses. Interestingly, TE events in this study occurred in both venous and arterial systems as has been previously described,[7,13,17] confirming that TE is not restricted to the venous system in PNH.

The TE event rate without eculizumab of 7.37 events per 100 patient-years in our patient population, which comprised 195 patients, is more than twice that of the TE event rate published previously for 67 high-risk patients in a single-center descriptive study.[8] The current TE event assessment was systematic, protocol specified, and performed on a multicenter, multinational, and controlled basis. While most patients in the current study had large populations of PNH granulocytes, TE was also observed before eculizumab in patients who would be expected to have less severe disease with smaller PNH cell populations (< 50%), as has been previously reported.[7,8] The observed variability in the pre-eculizumab TE event rates among the individual studies may be related in part to the different inclusion criteria. For example, the higher pretreatment TE event rate in the SHEPHERD study could reflect inclusion of patients with lower platelet counts that may be due to defective hematopoiesis or platelet consumption as a result of hypersplenism associated with previous thrombosis in the portal system.[22] Despite heterogeneity in the individual prestudy TE event rates, eculizumab treatment consistently resulted in a marked reduction in this rate in each individual study. It is important to note that the TE event rate was higher in the 12-month period immediately preceding eculizumab treatment. The increasing TE event rate of 17.21 events per 100 patient-years observed in the study population immediately prior to trial enrollment may indicate that the overall event rate of 7.37 TE events per 100 patient-years may have been diminished due to the loss of patients who had suffered fatal TE events and did not survive to enroll in the clinical trials or the progression of underlying disease.

The observed reduction of TE events during eculizumab treatment is unlikely to be due to improvements in patient care or more aggressive antithrombotic therapy leading up to and during the clinical studies since the TE event rate did not decrease in the period of time immediately preceding study enrollment or during the study in placebo-treated patients. The pre-eculizumab TE event rate during the 12-month period just prior to study initiation was markedly elevated, reaching a rate of 17.21 events per 100 patient-years. In addition, the TE event rate in placebo-treated patients from the double-blind placebo-controlled TRIUMPH study increased from 2.34 events per 100 patient-years before entering the study to 4.38 events per 100 patient-years during the 6-month evaluation period. Further, initiation of antithrombotic therapy during eculizumab treatment did not contribute to the

Table 3. Thromboembolism events in patients with and without eculizumab

TE events	Pilot*	TRIUMPH		SHEPHERD	Extension† (all studies)
		Placebo group	Eculizumab group		
Before treatment					
Patients, no.	11	44	43	97	195
TE events, no.	5	11	16	91	124
Patient-years, no.	161.7	470.4	309.0	718.3	1683.4
TE event rate, no. per 100 patient-years	3.09	2.34	5.18	12.67	7.37
Eculizumab treatment‡					
Patients, no.	11	44	43	97	195
TE events, no.	0	1	0	2	3§
Patient-years, no.	34.2	22.9	21.8	96.9	281.0
TE event rate, no. per 100 patient-years	0.00	4.38	0.00	2.06	1.07‖

*Includes a 1-year and a 2-year extension study.

†Includes TRIUMPH placebo-treated patients who transitioned to eculizumab treatment in the phase 3 extension study.

‡Three of 195 patients began anticoagulant treatment during eculizumab, 2 of whom started the treatment after a TE event.

§The 3 TE events occurring during eculizumab treatment included 2 events during SHEPHERD and 1 event during the extension.

‖$P < .001$ for comparisons of eculizumab treatment versus before treatment, signed rank test.

Table 4. Thromboembolism events in patients during the eculizumab treatment period compared with TE events during the same period of time before eculizumab treatment

TE events	Pilot*	TRIUMPH	SHEPHERD	Extension† (all studies)
Before treatment				
Patients, no.	11	43	97	195
Patient-years, no.	33.0	21.8	93.6	272.1
TE events	5	0	21	39
Eculizumab treatment				
Patients, no.	11	43	97	195
Patient-years, no.	34.2	21.8	96.9	281.0
TE events	0.00	0.00	2	3‡

*Includes a 1-year and a 2-year extension study.

†Includes TRIUMPH placebo-treated patients who transitioned to eculizumab treatment in the phase 3 extension study.

‡$P < .001$ for comparisons of eculizumab treatment versus before treatment, signed rank test.

Table 5. Thromboembolism events in patients receiving previous antithrombotics

TE events	Pilot*	TRIUMPH	SHEPHERD	Extension† (all studies)
Before treatment				
Patients, no.	9	23	51	103
TE events, no.‡	4	9	26	40
Patient-years, no.	45.3	70.6	168.2	377.1
TE event rate, no. per 100 patient-years	8.83	12.74	15.46	10.61
Eculizumab treatment				
Patients, no.	9	23	51	103
TE events, no.	0	0	0	1
Patient-years, no.	28.8	11.9	51.0	161.9
TE event rate, no. per 100 patient-years	0.00	0.00	0.00	0.62§

*Includes a 1-year and a 2-year extension study.

†Includes TRIUMPH placebo-treated patients who transitioned to eculizumab treatment in the phase 3 extension study.

‡To qualify as a TE event on antithrombotic therapy, the event must have been verified to have occurred more than 2 weeks following initiation of antithrombotics.

§$P < .001$ for comparisons of eculizumab treatment versus before treatment, signed rank test.

observed reduction in TE events; only 3 of 195 patients commenced antithrombotic treatment after eculizumab initiation.

Three TE events occurred in patients during eculizumab treatment: a deep vein thrombosis occurred after 1 year of eculizumab therapy in an anticoagulated patient with no history of TE; a pulmonary embolism occurred within 2 months of starting eculizumab therapy in a nonanticoagulated patient with a history of 2 previous TE events (pulmonary embolism and deep vein thrombosis); and a deep vein thrombosis occurred within 6 months of starting eculizumab therapy in a nonanticoagulated patient with a history of 1 TE event (deep vein thrombosis). Hemolysis was effectively controlled in all 3 patients during eculizumab treatment.

Anticoagulation is commonly used in patients with PNH who have a history of thrombosis and has been proposed as a prophylaxis for higher risk patients.[2,8] However, physicians have reported new TE events and advancing TE in patients with PNH while on antithrombotics.[7,8,14] In addition, hemorrhagic adverse events are a significant risk of chronic anticoagulant therapy particularly as some patients are thrombocytopenic, and therefore primary prophylaxis may be contraindicated in this patient population. Chronic anticoagulation was shown to be associated with an overall risk of 7.6 bleeding complications per 100 patient-years with the risk increasing to 11.0 bleeding complications per 100 patient-years during the first 90 days of treatment.[23] The risk for hemorrhage with anticoagulant therapy in patients with PNH has been reported to be approximately 5% or higher, including fatal hemorrhage.[8,14] In the present study, the pre-eculizumab TE event rate remained elevated in patients treated either therapeutically or prophylactically with antithrombotics, such as warfarin, suggesting that such therapies were not adequate to prevent TE in this patient population. By contrast, chronic administration of eculizumab, a therapy that targets the underlying hemolysis in PNH, significantly reduced the overall TE event rate. Whether anticoagulants can be reduced or eliminated in patients with PNH receiving eculizumab is the subject of future investigation. Further, while eculizumab discontinuation in 16 study patients has not been associated with hemolysis above pretreatment levels and concomitant thrombosis, patients should be monitored following eculizumab discontinuation.[24]

The pretreatment TE event rate was elevated, and substantial improvement with eculizumab was observed, even in patients who would be expected to have less severe disease. The TE event rate was reduced from 10.76 events per 100 patient-years before treatment to 2.88 events per 100 patient-years during eculizumab in patients with lower levels of baseline hemolysis (lowest pretreatment LDH quartile). Similarly, the TE event rate was reduced from 4.87 events per 100 patient-years before treatment to 0.00 events per 100 patient-years during eculizumab in patients with minimal pretreatment anemia (0 or 1 transfusion in the year prior to eculizumab treatment). Taken together, these data demonstrate that thrombotic risk is elevated in patients who would be expected to have less severe disease and the benefit of eculizumab in this patient population is maintained.

Hemolysis is characteristic of various hemolytic diseases and has been reported to contribute to serious clinical consequences. In patients with PNH, thromboembolic events have been linked to hemolysis, potentially through the buildup of cell-free plasma hemoglobin.[1,6-9] The effect of free hemoglobin on platelet function and hypercoagulability and the recognized increase in thrombotic tendencies in PNH may be largely due to its ability to scavenge nitric oxide.[25-32] Other potential mechanisms of thrombosis in PNH include the generation of procoagulant platelet microvesicles due to the absence of the terminal complement inhibitor CD59, and the interaction of red cell microvesicles and soluble urokinase plasminogen activator receptor.[11,12,33,34] Terminal complement inhibition with eculizumab would be expected to have a beneficial effect on TE occurring through any of these mechanisms.

The current findings show that long-term administration of eculizumab, in a diverse population of patients, including patients who would be expected to have less severe disease, substantially reduces the risk of thrombosis. In clinical studies to date, eculizumab therapy has controlled hemolysis, improved anemia and quality of life, and appeared to be safe and well tolerated.[18,19,35] Considering that thrombosis has been demonstrated to cause the majority of deaths in PNH, it is reasonable to expect that eculizumab treatment, by decreasing the risk of thrombosis, may increase the life expectancy of these patients.

Acknowledgments

The studies described in these analyses were funded by Alexion Pharmaceuticals.

We are indebted to Christopher Mojcik, MD, PhD, Henk-Andre Kroon, MD, MBA, Michael Bombara, BS, and Jing Jing Wang, MD, MS (Alexion Pharmaceuticals) for trial oversight; to Jason Chan, PhD (Alexion Pharmaceuticals) for the statistical analysis;

and to Kerry Quinn-Senger, PhD (Alexion Pharmaceuticals) for assistance with technical writing.

Additional investigators and institutions who participated in the clinical studies can be found in Document S1 (available on the *Blood* website; see the Supplemental Materials link at the top of the online article).

Authorship

Contribution: P.H. designed the study, performed research, collected, analyzed, and interpreted data, and drafted the paper; P.M., L.L., H.S., J. Szer, and R.A.B. performed research, collected, analyzed, and interpreted data, and reviewed the paper; U.D., A.M.R., and A.H. performed research, collected data, and reviewed the paper; J. Schubert, and N.S.Y. designed the study, performed research, collected, analyzed, and interpreted data, and reviewed the paper; G.S. analyzed and interpreted data, and drafted and reviewed the paper; M.B. designed the study, performed research, collected data, and reviewed the paper; S.A.R. designed the study, analyzed and interpreted data, and reviewed the paper; and L.B. and R.P.R. designed the study, analyzed and interpreted data, and drafted and reviewed the paper.

Conflict-of-interest disclosure: P.H., P.M., and G.S. have received grant support from Alexion Pharmaceuticals. P.H., A.M.R., J. Schubert, H.S., R.A.B., G.S., L.L., and A.H. have received lecture fees from Alexion Pharmaceuticals. P.H., J. Schubert, and M.B. have served as consultants for Alexion Pharmaceuticals. P.H., P.M., A.H., J. Schubert, and L.L. have served on Advisory Committees for Alexion Pharmaceuticals. S.A.R., L.B., and R.P.R. are employees of Alexion Pharmaceuticals and have equity ownership in the company. They have assigned to Alexion Pharmaceuticals their inventions made as employees and have received no royalties from the company for these inventions. All other authors declare no competing financial interests.

Correspondence: Peter Hillmen, Department of Haematology, Leeds General Infirmary, Great George Street, Leeds, LS1 3EX, United Kingdom; e-mail: peter.hillmen@nhs.net.

References

1. Rother RP, Bell L, Hillmen P, Gladwin MT. The clinical sequelae of intravascular hemolysis and extracellular plasma hemoglobin: a novel mechanism of human disease. JAMA. 2005;293:1653-1662.
2. Parker C, Omine M, Richards S, et al. Diagnosis and management of paroxysmal nocturnal hemoglobinuria. Blood. 2005;106:3699-3709.
3. Brodsky RA. Paroxysmal nocturnal hemoglobinuria. In: Hoffman R, Benz EJ Jr, Shattil S, Furie B, Cohen H, eds. Hematology: Basic Principles and Practice. Philadelphia, PA: Churchill Livingstone; 2005:419-427.
4. Luzzatto L, Araten DJ. Paroxysmal nocturnal hemoglobinuria. In: Young NS, Gerson SL, High KA, eds. Clinical Hematology. Philadelphia, PA: Mosby; 2006:326-339.
5. Young NS. Paroxysmal nocturnal hemoglobinuria: current issues in pathophysiology and treatment. Curr Hematol Rep. 2005;4:103-109.
6. Gralnick HR, Vail M, McKeown LP, et al. Activated platelets in paroxysmal nocturnal haemoglobinuria. Br J Haematol. 1995;91:697-702.
7. Audebert HJ, Planck J, Eisenburg M, Schrezenmeier H, Haberl RL. Cerebral ischemic infarction in paroxysmal nocturnal hemoglobinuria report of 2 cases and updated review of 7 previously published patients. J Neurol. 2005;252:1379-1386.
8. Hall C, Richards S, Hillmen P. Primary prophylaxis with warfarin prevents thrombosis in paroxysmal nocturnal hemoglobinuria (PNH). Blood. 2003;102:3587-3591.
9. Rosse WF, Nishimura J. Clinical manifestations of paroxysmal nocturnal hemoglobinuria: present state and future problems. Int J Hematol. 2003; 77:113-120.
10. Luzzatto L, Gianfaldoni G. Recent advances in biological and clinical aspects of paroxysmal nocturnal hemoglobinuria. Int J Hematol. 2006;84: 104-112.
11. Wiedmer T, Hall SE, Ortel TL, et al. Complement-induced vesiculation and exposure of membrane prothrombinase sites in platelets of paroxysmal nocturnal hemoglobinuria. Blood. 1993;82:1192-1196.
12. Sims PJ, Rollins SA, Wiedmer T. Regulatory control of complement on blood platelets: modulation of platelet procoagulant responses by a membrane inhibitor of the C5b-9 complex. J Biol Chem. 1989;264:19228-19235.
13. Hillmen P, Lewis SM, Bessler M, Luzzatto L, Dacie JV. Natural history of paroxysmal nocturnal hemoglobinuria. N Engl J Med. 1995;333:1253-1258.
14. Moyo VM, Mukhina GL, Garrett ES, Brodsky RA. Natural history of paroxysmal nocturnal haemoglobinuria using modern diagnostic assays. Br J Haematol. 2004;126:133-138.
15. Socié G, Mary JY, de Gramont A, et al. Paroxysmal nocturnal haemoglobinuria: long-term follow-up and prognostic factors: French Society of Haematology. Lancet. 1996;348:573-577.
16. Araten DJ, Thaler HT, Luzzatto L. High incidence of thrombosis in African-American and Latin-American patients with paroxysmal nocturnal haemoglobinuria. Thromb Haemost. 2005;93:88-91.
17. Nishimura J, Kanakura Y, Ware RE, et al. Clinical course and flow cytometric analysis of paroxysmal nocturnal hemoglobinuria in the United States and Japan. Medicine (Baltimore). 2004;83: 193-207.
18. Hillmen P, Young NS, Schubert J, et al. The complement inhibitor eculizumab in paroxysmal nocturnal hemoglobinuria. N Engl J Med. 2006; 355:1233-1243.
19. Hillmen P, Hall C, Marsh JC, et al. Effect of eculizumab on hemolysis and transfusion requirements in patients with paroxysmal nocturnal hemoglobinuria. N Engl J Med. 2004;350:552-559.
20. Young NS, Antonioli E, Rotoli B, et al. Safety and efficacy of the terminal complement inhibitor eculizumab in patients with paroxysmal nocturnal hemoglobinuria: Interim Shepherd Phase III Clinical Study [abstract]. Blood. 2006;108:971.
21. World Health Organization. WHO Drug Dictionary. Uppsala Monitoring Center; 2001. Uppsala, Sweden.
22. Bayraktar Y, Harmanci O. Etiology and consequences of thrombosis in abdominal vessels. World J Gastroenterol. 2006;12:1165-1174.
23. Palareti G, Leali N, Coccheri S, et al. Bleeding complications of oral anticoagulant treatment: an inception-cohort, prospective collaborative study (ISCOAT): Italian Study on Complications of Oral Anticoagulant Therapy. Lancet. 1996;348:423-428.
24. Alexion Pharmaceuticals, Inc. Soliris (eculizumab) full prescribing information. Washington, DC: United States Food and Drug Administration; March 16, 2007. Rockville, Maryland.
25. Reiter CD, Wang X, Tanus-Santos JE, et al. Cell-free hemoglobin limits nitric oxide bioavailability in sickle-cell disease. Nat Med. 2002;8:1383-1389.
26. Olson JS, Foley EW, Rogge C, et al. NO scavenging and the hypertensive effect of hemoglobin-based blood substitutes. Free Radic Biol Med. 2004;36:685-697.
27. Radomski MW, Palmer RM, Moncada S. Endogenous nitric oxide inhibits human platelet adhesion to vascular endothelium. Lancet. 1987;2:1057-1058.
28. Radomski MW, Palmer RM, Moncada S. The anti-aggregating properties of vascular endothelium: interactions between prostacyclin and nitric oxide. Br J Pharmacol. 1987;92:639-646.
29. Megson IL, Sogo N, Mazzei FA, et al. Inhibition of human platelet aggregation by a novel S-nitrosothiol is abolished by haemoglobin and red blood cells in vitro: implications for anti-thrombotic therapy. Br J Pharmacol. 2000;131:1391-1398.
30. Olsen SB, Tang DB, Jackson MR, et al. Enhancement of platelet deposition by cross-linked hemoglobin in a rat carotid endarterectomy model. Circulation. 1996;93:327-332.
31. Broekman MJ, Eiroa AM, Marcus AJ. Inhibition of human platelet reactivity by endothelium-derived relaxing factor from human umbilical vein endothelial cells in suspension: blockade of aggregation and secretion by an aspirin-insensitive mechanism. Blood. 1991;78:1033-1040.
32. Schäfer A, Wiesmann F, Neubauer S, et al. Rapid regulation of platelet activation in vivo by nitric oxide. Circulation. 2004;109:1819-1822.
33. Leone G, Sica S, Chiusolo P, Teofili L, De Stefano V. Blood cells diseases and thrombosis. Haematologica. 2001;86:1236-1244.
34. Sloand EM, More K, Shah S, et al. Soluble urokinase plasminogen activator receptor is increased in patients with paroxysmal nocturnal hemoglobinuria (PNH) and thrombosis and inhibits plasmin generation in vitro and promotes thrombosis in the mouse model [abstract]. Blood. 2006;108: 1460.
35. Hill A, Hillmen P, Richards SJ, et al. Sustained response and long-term safety of eculizumab in paroxysmal nocturnal hemoglobinuria. Blood. 2005;106:2559-2565.

2007 110: 4123-4128
doi:10.1182/blood-2007-06-095646 originally published online August 16, 2007

Effect of the complement inhibitor eculizumab on thromboembolism in patients with paroxysmal nocturnal hemoglobinuria

Peter Hillmen, Petra Muus, Ulrich Dührsen, Antonio M. Risitano, Jörg Schubert, Lucio Luzzatto, Hubert Schrezenmeier, Jeffrey Szer, Robert A. Brodsky, Anita Hill, Gerard Socié, Monica Bessler, Scott A. Rollins, Leonard Bell, Russell P. Rother and Neal S. Young

Blood (print ISSN 0006-4971, online ISSN 1528-0020), is published weekly by the American Society of Hematology, 2021 L St, NW, Suite 900, Washington DC 20036.