Safety, Pharmacokinetic, and Functional Effects of the Nogo-A Monoclonal Antibody in Amyotrophic Lateral Sclerosis: A Randomized, First-In-Human Clinical Trial

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Safety, Pharmacokinetic, and Functional Effects of the Nogo-A Monoclonal Antibody in Amyotrophic Lateral Sclerosis: A Randomized, First-In-Human Clinical Trial

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Abstract

The neurite outgrowth inhibitor, Nogo-A, has been shown to be overexpressed in skeletal muscle in amyotrophic lateral sclerosis (ALS); it is both a potential biomarker and therapeutic target. We performed a double-blind, two-part, dose-escalation study, in subjects with ALS, assessing safety, pharmacokinetics (PK) and functional effects of ozanezumab, a humanized monoclonal antibody against Nogo-A. In Part 1, 40 subjects were randomized (3:1) to receive single dose intravenous ozanezumab (0.01, 0.1, 1, 5, or 15 mg/kg) or placebo. In Part 2, 36 subjects were randomized (3:1) to receive two repeat doses of intravenous ozanezumab (0.5, 2.5, or 15 mg/kg) or placebo, approximately 4 weeks apart. The primary endpoints were safety and tolerability (adverse events [AEs], vital signs, electrocardiogram [ECG], and clinical laboratory tests). Secondary endpoints included PK, immunogenicity, functional endpoints (clinical and electrophysiological), and biomarker parameters. Overall, ozanezumab treatment (0.01–15 mg/kg) was well tolerated. The overall incidence of AEs in the repeat dose 2.5 mg/kg and 15 mg/kg ozanezumab groups was higher than in the repeat dose placebo group and repeat dose 0.5 mg/kg ozanezumab group. The majority were considered not related to study drug by the investigators. Six serious AEs were reported in three subjects receiving ozanezumab; none were considered related to study drug. No study drug-related patterns were identified for ECG, laboratory, or vital signs parameters. One subject (repeat dose 15 mg/kg ozanezumab) showed a weak, positive anti-ozanezumab-antibody result. PK results were generally consistent with monoclonal antibody treatments. No apparent treatment effects were observed for functional endpoints or muscle biomarkers. Immunohistochemical staining showed dose-dependent co-localization of ozanezumab with Nogo-A in skeletal muscle. In conclusion, single and repeat dose ozanezumab treatment was well tolerated and demonstrated co-localization at the site of action. These findings support future studies with ozanezumab in ALS.

Trial Registration: ClinicalTrials.gov NCT00875446 GSK-ClinicalStudyRegister.com GSK ID 111330


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Introduction

Amyotrophic lateral sclerosis (ALS) is characterized by selective and progressive loss of upper motor neurons of the motor cortex and lower motor neurons of the brainstem and spinal cord.[1–3] The main manifestations of ALS are progressive widespread muscle weakness and atrophy, leading to severe motor disability that affects speech, swallowing, respiratory function, and the extremities.[4] Cognitive impairment, predominantly in the form of executive dysfunction, may be detected in around 50% of patients, with up to 15% experiencing frontotemporal dementia.[5] Most patients die within 5 years of onset.[1,4]

Excitotoxicity, i.e. an excessive drive of glutamate, is considered to be one of the mechanisms of neurodegeneration in ALS.[6] Riluzole, the only currently approved drug that alters survival in ALS, is thought to reduce excessive glutamatergic drive on neurons.[3,7] Although the exact mechanism of action of riluzole is unclear, it is likely to involve several components, including inhibition of glutamate release, blockade of calcium and sodium channels, modulation of γ-Aminobutyric acid (GABA) transmission, as well as effects on N-Methyl-D-aspartate (NMDA) or α-Amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid (AMPA) receptors.[7–9]

Nogo-A, a negative regulator of neuronal growth, is a potent neurite outgrowth inhibitor in the adult central nervous system and is expressed by oligodendrocytes.[10,11] Outside the central nervous system Nogo-A is overexpressed in the skeletal muscle of the superoxide dismutase 1 (SOD1) transgenic mouse model of ALS, as well as in human skeletal muscle, as demonstrated in biopsies taken from patients with ALS.[12] Nogo-A expression in skeletal muscle has been proposed as an early diagnostic biomarker of ALS, with the level of expression reported to correlate with disease severity.[12–14] This view is challenged by reports suggesting that Nogo-A is a marker of muscle denervation rather than ALS specifically, noted to be up-regulated in muscle in preclinical denervation models and in muscle biopsies from subjects with a range of myopathies and peripheral neuropathies.[15–18] In the SOD1 transgenic mouse genetic ablation of Nogo-A prolonged survival and reduced muscle denervation,[19] while overexpression of Nogo-A in muscle fibers of mice induced neuromuscular junction instability and promoted denervation.[19] There is therefore a strong rationale for testing antibodies against Nogo-A in ALS. It is anticipated that blockade of Nogo-A may inhibit neurite retraction and potentially slow the axonal degeneration pattern in lower motor neurons that begins at the neuromuscular junction.[20] This may enhance motor neuron-muscle coupling, leading to functional improvement and survival benefits in patients with ALS.

Ozanezumab (GSK1223249: GlaxoSmithKline) is a humanized monoclonal antibody against Nogo-A, which is currently being investigated for the treatment of ALS. Ozanezumab has two possible modes of action: preventing binding of Nogo-A to the Nogo-A receptor and/or Nogo-A down-regulation by antibody-induced internalization of cell surface Nogo-A.[21]

Given that the anticipated mechanism of action of ozanezumab is via Nogo-A, which is not appreciably expressed in skeletal muscle under physiological conditions but is overexpressed in ALS, it was felt that conduct of a study in healthy subjects would not adequately reveal the potential risks or effects of treatment. Therefore, the first-in-human, Phase I/IIa study presented here was performed in subjects with ALS to assess the safety, pharmacokinetic (PK), and functional and biomarker effects of ozanezumab.

Methods

Study design

This was a randomized, placebo-controlled, double-blind, single and repeat dose-escalation, two-part study in subjects with ALS, conducted at 11 sites in France, Italy, the UK, and the USA, between May 2009 and September 2011. Screening took place within 28 days of the first dose of investigational product. In Part 1, escalating single doses (SD) of ozanezumab (0.01, 0.1, 1, 5, or 15 mg/kg administered intravenously [IV]), were evaluated in five sequential subject cohorts (8 subjects per cohort, randomized 3:1 to receive ozanezumab or placebo). Part 2 was also of a sequential dose-escalating design: 36 subjects across three cohorts (12 subjects per cohort) were randomized (3:1) to receive two repeat doses (RD) of ozanezumab (0.5, 2.5, or 15 mg/kg administered IV) or placebo, approximately 4 weeks apart. IV infusions were given over 60 minutes except for the 0.01 mg/kg dose, which was given over 11.2 minutes. Key safety data were reviewed by a blinded Dose Escalation Committee (comprising GlaxoSmithKline staff and an external expert neurologist who was experienced in ALS) before proceeding to the next dosing cohort. To ensure tolerability before proceeding, the first four subjects in all cohorts of Part 1 and the first cohort of Part 2 received treatment on consecutive days, so that only one subject was randomized and dosed within any 24-hour period. Dosing of all other subjects was not staggered. The follow-up period was at least 12 weeks for all subjects. Subjects in Part 2 were followed-up for 16 weeks and subjects receiving 15 mg/kg ozanezumab were followed-up for immuno-genicity for 16–20 weeks.

Ethics statement

The study protocol, protocol amendments, and informed consent were approved by a national, regional or investigational center ethics committee or an institutional review board (IRB); at each of the participating sites: Comité de Protection des Personnes Ile-de-France VI, Hôpital La Pitié-Salpêtrière, Paris, France; Comitato Etico per la Sperimentazione, Azienda Ospedaliera Universitaria Integrata di Verona, Italy; Guy’s Research Ethics Committee, St. Thomas Hospital, London, UK; Carolinas Healthcare System IRB, North Carolina; Wake Forest University.
Health Sciences, IRB, North Carolina; Johns Hopkins Medicine IRBs, Maryland; Western IRB, Washington; IRB, Weill Cornell Medical Center, New York; and IRB for the Protection of Human Subjects, SUNY Upstate Medical University, New York, USA. This study was conducted in accordance with Good Clinical Practice and the guiding principles of the Declaration of Helsinki, and all subjects provided written informed consent. This study is registered at clinicaltrials.gov (NCT00875446) and at http://www.gsk-clinicalstudyregister.com (GSK ID 111330). The protocol for this trial and supporting CONSORT checklist are available as supporting information; see Checklist S1 and Protocol S1.

Randomization and masking

Subjects in each cohort were centrally randomized across all sites via an Interactive Voice Response System. The randomization schedule was computer-generated using the validated in-house RandAll system. Infusions were prepared by a non-blinded pharmacist at the study site and infusion lines were masked in order to maintain the study blind.

Patients

Eligible subjects were male or female of non-childbearing potential, 18–80 years of age, with a diagnosis of possible, laboratory-supported probable, probable or definite familial or sporadic ALS according to The Revised El Escorial diagnostic criteria,[22] and onset of muscle weakness within 60 months of study entry. Each subject was only allowed to participate in one part of the study. Subjects were also required to have a slow inspiratory vital capacity (SVC) ≥70% of predicted (changed by protocol amendment to include those with SVC <70% at the discretion of the investigator, as long as they did not show respiratory insufficiency). Medications (including riluzole) were required to have been stable within 28 days prior to dosing. Main exclusion criteria were: neuromuscular disorders (in addition to ALS, that could have impacted the study outcomes), dementia or psychiatric illnesses, that may have affected either outcome measures or patient understanding and/or compliance with the study requirements and procedures; positive alcohol or drugs tests at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screening or a history of excessive alcohol consumption; vaccination within 3 weeks of study drug administration (originally at screen...
baseline characteristics are presented in Figure 1. Across all subjects, the mean age was 58 years, mean body mass index was 26.2 kg/m², and the majority of subjects were white males (Table 1). The majority of subjects had sporadic ALS (69/76; 91%) with a mean time from diagnosis of 11.1 months and a mean time from onset of muscle weakness of 19.4 months; the mean time from onset of muscle weakness varied considerably between these cohorts (Table 1). Fifty-nine (78%) subjects (35/40 and 24/36 in the SD and RD cohorts, respectively) were taking riluzole.

**Safety**

Overall, ozanezumab was well tolerated. Forty-seven (62%) subjects across all cohorts (35/57 [61%] on active treatment, 12/19 [63%] on placebo) reported at least one AE (Table 2). The proportion of subjects who reported ≥1 AE in the ozanezumab groups was similar when compared with the placebo group (61% and 63%, respectively) although the overall incidence of AEs in the RD 2.5 mg/kg and 15 mg/kg ozanezumab groups (78% and 89% of subjects with any AE, respectively) was higher than in the RD placebo group (56%) and the RD 0.5 mg/kg ozanezumab group (44%). Most AEs were of mild or moderate intensity as judged by the investigator. Seven (9%) subjects (5/57 [8.8%] on active treatment, 2/19 [10.5%] on placebo) reported eight AEs of severe intensity. Among the severe AEs, three subjects experienced severe headache. Two of these were in placebo groups. The third subject reported onset of headache 9 days after receiving the first dose of ozanezumab (RD 2.5 mg/kg group); this was resolved after 6 days and was not considered related to treatment. Another subject experienced severe dysphagia (RD 15 mg/kg ozanezumab), which was unresolved at the end of the study and considered not related to study drug. The remaining four severe AEs in three subjects were classed as SAEs.

Thirty-two AEs (29 mild, one moderate, one severe, and one of unknown severity), that were considered possibly related to the study medication, were reported by eight subjects (Table 2). None resulted in withdrawal from the study. Most common AEs (reported in ≥4 subjects across all cohorts) were back pain, bronchitis, fall, headache and procedural pain at biopsy site (Table 2). AEs in the cardiac disorders category were reported in four subjects. One of these, sinus tachycardia of mild intensity, was considered possibly related to investigational product (RD 2.5 mg/kg ozanezumab). Other events, not considered related to study drug, included ventricular extrasystoles (SD 5 mg/kg ozanezumab), which resolved after 2 hours, with the subject remaining asymptomatic with no findings of clinical concern on Holter monitoring; second degree atrioventricular block (RD 2.5 mg/kg ozanezumab); and cardiac arrest and cardio-respiratory arrest, as described under SAEs below.

Six SAEs were reported in three subjects receiving ozanezumab, all considered by the investigators as unrelated to study medication. One subject (SD 15 mg/kg ozanezumab) suffered a head injury after an accidental fall, which led to hospitalization and ultimately resolved. The second subject (SD 5 mg/kg ozanezumab) experienced excess bronchial secretions resulting in hospitalization, and later died from respiratory failure, 17 weeks after the dosing. The third subject (RD 2.5 mg/kg ozanezumab) was hospitalized for abdominal pain, for which the etiology remained elusive; this subject later died from cardiac arrest and cardio-respiratory arrest 10.5 weeks after the second dose.

The events common to ALS showed no patterns of reporting to suggest an adverse drug effect on the underlying condition. The most frequently reported event common to ALS was weakness, occurring in 8/19 (42%) and 19/57 (33%) subjects in the placebo and ozanezumab groups, respectively.

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**Figure 1. Subject disposition flow diagram for Parts 1 and 2.** N, total number of subjects in group; n, number of subjects in category; PK, pharmacokinetics; SAE, serious adverse events. Two doses, received 4 weeks apart.

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Table 1. Subject demographics and baseline characteristics.

<table>
<thead>
<tr>
<th>Demographics</th>
<th>Placebo SD n=10</th>
<th>Ozanezumab SD n=9</th>
<th>Placebo RD n=9</th>
<th>Ozanezumab RD+ n=9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age in years, mean (STDV)</td>
<td>54.7 (11.38)</td>
<td>56.8 (9.47)</td>
<td>59.2 (11.64)</td>
<td>62.2 (6.15)</td>
</tr>
<tr>
<td>Sex (male), n (%)</td>
<td>7 (70)</td>
<td>4 (67)</td>
<td>5 (83)</td>
<td>6 (100)</td>
</tr>
<tr>
<td>BMI in kg/m², mean (STDV)</td>
<td>24.69 (2.853)</td>
<td>27.70 (4.205)</td>
<td>25.90 (1.973)</td>
<td>28.13 (5.311)</td>
</tr>
<tr>
<td>Race; n (%)</td>
<td>10 (100)</td>
<td>6 (100)</td>
<td>6 (100)</td>
<td>6 (83)*</td>
</tr>
<tr>
<td>Familial ALS, n (%)</td>
<td>1 (10)</td>
<td>1 (17)</td>
<td>1 (17)</td>
<td>0</td>
</tr>
<tr>
<td>Sporadic ALS, n (%)</td>
<td>9 (90)</td>
<td>5 (83)</td>
<td>5 (83)</td>
<td>6 (100)</td>
</tr>
<tr>
<td>Bulbar onset ALS, n (%)</td>
<td>0</td>
<td>1 (17)</td>
<td>0</td>
<td>1 (17)</td>
</tr>
<tr>
<td>Limb onset ALS, n (%)</td>
<td>10 (100)</td>
<td>5 (83)</td>
<td>5 (83)</td>
<td>6 (100)</td>
</tr>
<tr>
<td>Mean (STDV) time since onset</td>
<td>10.7 (7.85)</td>
<td>9.7 (6.69)</td>
<td>9.7 (9.81)</td>
<td>9.7 (9.81)</td>
</tr>
<tr>
<td>of muscle weakness, months</td>
<td>17.2 (14.37) [2, 31.4 (19.35) [1, 5, 34]</td>
<td>15.0 (3.95) [3, 21]</td>
<td>15.0 (3.95) [3, 21]</td>
<td>16.4 (9.81) [1, 34]</td>
</tr>
<tr>
<td>Mean (STDV) time since ALS</td>
<td>8.6 (4.85)</td>
<td>6.2 (2.64)</td>
<td>9.7 (9.69)</td>
<td>9.7 (9.81)</td>
</tr>
<tr>
<td>diagnosis, months</td>
<td>10.7 (7.85)</td>
<td>9.7 (6.69)</td>
<td>9.7 (9.81)</td>
<td>9.7 (9.81)</td>
</tr>
<tr>
<td>Mean (STDV) ALSFRS-R score</td>
<td>35.0 (5.60)</td>
<td>38.3 (4.08)</td>
<td>38.8 (5.42)</td>
<td>38.0 (5.66)</td>
</tr>
</tbody>
</table>

*Two doses, received 4 weeks apart.
†Remaining patient was of African American/African heritage. ALS, amyotrophic lateral sclerosis; ALSFRS-R, ALS functional rating scale-revised; BMI, body mass index; n, number of subjects; STDV, standard deviation; SD, single dose; RD, repeated dose.

doi:10.1371/journal.pone.0097803.t001
Table 2. Summary of adverse events in Part 1 (SD) and Part 2 (RD).

<table>
<thead>
<tr>
<th>Preferred term</th>
<th>Placebo SD</th>
<th>Ozanezumab SD</th>
<th>Placebo RD</th>
<th>Ozanezumab RD**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n = 10</td>
<td>n = 6</td>
<td>n = 9</td>
<td>n = 9</td>
</tr>
<tr>
<td>Subjects with any AE, n (%)^*</td>
<td>7 (70)</td>
<td>2 (33)</td>
<td>5 (56)</td>
<td>7 (78)</td>
</tr>
<tr>
<td>Back pain</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bronchitis</td>
<td>2 (20)</td>
<td>1 (17)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Fall</td>
<td>2 (20)</td>
<td>1 (17)</td>
<td>2 (33)</td>
<td>1 (11)</td>
</tr>
<tr>
<td>Headache</td>
<td>1 (10)</td>
<td>0</td>
<td>1 (17)</td>
<td>1 (11)</td>
</tr>
<tr>
<td>Procedural pain</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Subjects with mild AEs</td>
<td>5 (50)</td>
<td>1 (17)</td>
<td>1 (17)</td>
<td>2 (22)</td>
</tr>
<tr>
<td>Subjects with moderate AEs</td>
<td>1 (10)</td>
<td>1 (17)</td>
<td>3 (50)</td>
<td>2 (22)</td>
</tr>
<tr>
<td>Subjects with severe AEs</td>
<td>1 (10)</td>
<td>0</td>
<td>1 (17)</td>
<td>3 (33)</td>
</tr>
<tr>
<td>Subjects with any drug-related AE, n (%)*</td>
<td>2 (2)</td>
<td>1 (17)</td>
<td>0</td>
<td>3 (33)</td>
</tr>
<tr>
<td>Asthenia</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Headache</td>
<td>0</td>
<td>0</td>
<td>1 (17)</td>
<td>1 (11)</td>
</tr>
<tr>
<td>Parasthesia</td>
<td>1 (10)</td>
<td>1 (17)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Procedural pain</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Subjects with serious AE, n (%)</td>
<td>0</td>
<td>0</td>
<td>1 (17)</td>
<td>1 (11)</td>
</tr>
</tbody>
</table>

Number of drug-related AEs | 2 | 1 (11) | 0 | 1 (11) |

Number of serious AEs | 0 | 0 | 2 | 0 |

*Only those occurring in ≥4 subjects across all cohorts are listed.

\*Five unreported AEs were identified (in 3 subjects): 1 subject experienced severe diarrhea (2.5 mg/kg), 1 subject experienced shoulder pain, secondary to muscle biopsy (15 mg/kg), and 1 subject experienced some minor skin bruising, a fall and a hard swelling on the left hip (resulting from the fall) (15 mg/kg).

\**Two doses, received 4 weeks apart.

\*Only those occurring in ≥2 subjects across all cohorts are listed. AE, adverse event; n, number of subjects; SD, single dose; RD, repeated dose.
study drug. However, neither event was considered related to the
subjects but none were considered clinically significant. Two
laboratory findings raised no safety concerns. See Results S1 for additional details of ALS and was not considered clinically relevant. Urinalysis findings occurred in four subjects receiving ozanezumab. The findings were based on random blood glucose samples. None of the elevated glucose values were considered
isolated cases of hyperglycemia were seen in patients who received levels of PCI, all of whom received ozanezumab; these elevations occurred at least 1 week after dosing in five of these subjects. Changes in heart rate were reported for a small number of subjects but none were considered clinically significant. Two
abnormalities occurred in four subjects across all treatment groups but this was observed in patients with creatine kinase levels were observed in a number of subjects across a bi-
proportional to dose, while concentrations declined in a bi-
exponential fashion, with a terminal elimination half-life of approximately 20 days (Table 3 and Figure 2).

Table 3. Ozanezumab pharmacokinetic parameters.

<table>
<thead>
<tr>
<th>Ozanezumab SD</th>
<th>0.01 mg/kg n = 6</th>
<th>0.1 mg/kg n = 6</th>
<th>1 mg/kg n = 6</th>
<th>5 mg/kg n = 6</th>
<th>15 mg/kg n = 6</th>
<th>Ozanezumab RD*</th>
<th>0.5 mg/kg n = 9</th>
<th>2.5 mg/kg n = 9</th>
<th>15 mg/kg n = 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tmax (h)</td>
<td>1.00 (0.98–1.00)</td>
<td>1.125 (1.00–10.05)</td>
<td>1.06 (1.00–23.17)</td>
<td>1.05 (0.05–1.18)</td>
<td>1.08 (1.01–10.00)</td>
<td>1.02 (1.00–24.00)</td>
<td>1.08 (1.00–6.03)</td>
<td>1.02 (0.07–10.00)</td>
<td>1.00 (1.00–6.10)</td>
</tr>
<tr>
<td>Cmax (µg/mL)</td>
<td>0.265 (17.9)</td>
<td>2.93 (27.7)</td>
<td>232 (22.8)</td>
<td>125 (28.0)</td>
<td>527 (18.3)</td>
<td>13.8 (17.0)</td>
<td>16.9 (36.2)</td>
<td>58.7 (22.8)</td>
<td>65.9 (23.2)</td>
</tr>
<tr>
<td>AUC0–Week 4 (µg.h/mL)</td>
<td>17.6 (15.4)</td>
<td>504 (27.2)</td>
<td>4647 (14.1)</td>
<td>23888 (28.0)</td>
<td>92776 (17.0)</td>
<td>2808 (20.9)</td>
<td>4063 (53.7)</td>
<td>10461 (36.4)</td>
<td>19133 (25.9)</td>
</tr>
<tr>
<td>Clearance (mL/h)</td>
<td>-</td>
<td>749 (25.5)</td>
<td>6723 (16.8)</td>
<td>32503 (31.7)</td>
<td>12839 (22.4)</td>
<td>-</td>
<td>5420 (44.7)</td>
<td>-</td>
<td>109904 (18.8)</td>
</tr>
<tr>
<td>t1/2 (days)</td>
<td>-</td>
<td>19.6 (0.6)</td>
<td>208 (0.8)</td>
<td>17.8 (0.8)</td>
<td>18.1 (0.8)</td>
<td>-</td>
<td>18.8 (1.3)</td>
<td>-</td>
<td>22.5 (0.9)</td>
</tr>
</tbody>
</table>

*Two doses, received 4 weeks apart. AUC0–Week 4, area under the plasma concentration-time curve up to Week 4; AUC0–∞, area under the plasma concentration-time curve up to infinity; Cmax, maximum observed plasma concentration; n, number of subjects; RD, repeated dose; SD, single dose; t1/2, apparent terminal phase half-life; Tmax, time at which Cmax was observed. Tmax presented as median (range); all other values presented as geometric mean of the log-transformed data (coefficient of variation, CV%).
placebo. However, a numerical difference in favor of ozanezumab versus placebo was observed in the RD 15 mg/kg group for each endpoint (Tables S5 and S6).

In MUNE data analysis, no trends between ozanezumab groups and placebo were observed (Table S6).

**Biomarkers**

There was no evidence of a pharmacological response with ozanezumab treatment on protein or RNA biomarkers.

Measurement of Nogo-A and ozanezumab using IHC staining of muscle biopsies suggested co-localization of the drug at the site of action in skeletal muscle. Co-localization followed a similar trend to ozanezumab levels in muscle, suggesting that this was related to exposure. Greater than 90% co-localization was observed with the 15 mg/kg dose, 8 days after dosing, with levels dropping below 90% at 3–4 weeks post-dose (Figure 3).

**Pharmacokinetic/functional endpoint relationship**

Following graphical exploration of a potential exposure-response relationship of ozanezumab for ALSFRS-R score (monthly rate of decline) at each post-baseline visit, no PK/functional endpoint relationship was identified.

**Discussion**

The effort to develop new treatments for ALS has led to repeated failure since the demonstration that riluzole extended survival.[3] Despite initially encouraging results from a Phase II trial, which suggested beneficial effects on ALSFRS-R and survival,[27] the recent negative results of the dexpramipexole Phase III study is yet another disappointing example.[28] Thus, there is still an urgent need for new treatments for ALS. A number of compounds targeting different aspects of ALS pathogenesis are...
Figure 3. Co-localization of membrane Nogo-A with ozanezumab in skeletal muscle of individual subjects. A. Triplicate readings are provided from biopsies in Cohort 7 and 8 (single reading from Cohort 5) dose 2 +D22–26, biopsy taken 22–26 days after the second dose; dose 1 +24H, biopsy taken 24 hours after first dose. B. Nogo-A (red), ozanezumab (green) and co-localization (yellow), in muscle biopsy, 24 hours post-dose. doi:10.1371/journal.pone.0097803.g003
Currently being investigated. This was the first study in humans of ozanezumab, a monoclonal antibody targeting Nogo-A.

Generally, the baseline characteristics were similar between treatment groups, however, as the inclusion criteria permitted a history of muscle weakness of up to 60 months, 8/76 (11%) patients reported having muscle weakness for 36 months or longer. This could have caused a bias towards long-term survivors and since the patient cohorts were small, the mean disease duration varied considerably between these cohorts.

Ozanezumab was generally well tolerated at single doses of 0.01–15 mg/kg and two repeat doses of 0.5–15 mg/kg, with no adverse drug effects on the underlying condition.

Although there was no clear relationship between reported AEs and increasing doses of ozanezumab, the overall incidence of AEs was numerically higher in the two higher dose RD cohorts compared with placebo and the lowest dose RD cohort. Despite the higher incidence of AEs in the RD cohorts, proportions of mild, moderate, and severe AEs were comparable. SAEs and deaths were not attributed to the study drug, though one cardiac non-serious AE (mild sinus tachycardia) was considered possibly related. There were no clinically significant safety laboratory findings and no clear patterns indicative of a treatment effect on ECG parameters or vital signs.

Following IV infusion, the plasma PK characteristics of ozanezumab were generally consistent with those of a humanized immunoglobulin G monoclonal antibody. One observation of note was the approximate 2-fold difference between SD and RD (first dose) ozanezumab 15 mg/kg in average C\text{max} and AUC values. Examination of the individual data suggested no overlap in values between the two cohorts. However, detailed investigations of drug substance, subject demographics, individual dosing records, and the PK plasma sample assay methodology revealed no explanation for this difference. Consequently, the difference appeared to be genuine, and possibly attributed to between-cohort variability.

This study was not statistically powered to detect changes in functional (clinical and electrophysiological) endpoints. Despite this, and despite subjects receiving only one or two doses each, a trend was observed for clinical endpoints such as ALSFRS-R, SVC, and MMT, which possibly suggested a response in the highest dose cohorts. Trends observed should be interpreted with great caution given the small sample size, and other studies will be required to confirm and further investigate these trends. The relationship between ozanezumab administration and pharmacological signal on protein or RNA requires further investigation; the current study may have been too short to detect such responses. In future studies, optimum time points, treatment times, and analysis methods will need to be established.

IHC staining of muscle biopsies suggested that there were dose-dependent changes in ozanezumab quantification and detection. In cohorts 2 and 8, ozanezumab distributed and co-localized with Nogo-A at the site of action in skeletal muscle. Following the full distribution of ozanezumab to muscle tissue and peak co-localization approximately 1 week after dosing, the percentage of co-localization appeared to be related to levels of ozanezumab, suggesting a possible relationship with exposure.

Overall, ozanezumab was well tolerated and PK parameters were generally consistent with those of humanized monoclonal antibodies. The trends observed on functional endpoints in the present study, along with the co-localization of ozanezumab in skeletal muscle, are encouraging; these observations, along with the lack of emerging safety signals, support future studies of ozanezumab in this devastating disease, and a Phase II study of efficacy and safety of ozanezumab (NCT01753076) is currently underway.

Supporting Information

Table S1 Assessment schedules for Part 1. AE, adverse event; ALSFRS-R, amyotrophic lateral sclerosis functional rating scale-revised; ECG, electrocardiogram; FU, follow-up; MUNE, motor unit number estimation; PK, pharmacokinetic; SAE, serious adverse event. *The precise timing of safety, functional assessments, and PK blood sampling may have been altered during the course of the study based on emerging data. If the profile indicated that more sampling or assessments were needed, additional time points were to be added. Study assessments to follow PK sampling at end of infusion. (The 1-hour PK sample was collected directly at the end of the infusion, Cohorts 2–8). †Only SAEs related to study participation were collected prior to the start of the investigational product. Once the investigational product infusion began, all AEs and SAEs were collected until the last FU visit. ‡Continuous Lead II ECG commenced approximately 1 hour pre-dose on Day 1 until 24 hours post-dose. ‡Muscle biopsies, which were voluntary collections in Cohort 3 (1 mg/kg) and required collections in Cohort 5 (15 mg/kg) were collected pre-dose and at Week 4. The pre-dose muscle biopsy was only to be done when the subject had passed all screening assessments and eligibility had been reconfirmed. This meant the pre-dose biopsy could be done at any appropriate time before Day 1. Blood samples at pre-dose and at Week 4 were collected regardless of whether or not a muscle biopsy was to be taken. The number and schedule of FU visits after Week 12 for each subject was to vary depending on plasma concentrations of ozanezumab reaching a low enough level to allow a final blood sample to have been assayed for immunogenicity.

(DOCX)

Table S2 Assessment schedules for Part 2. AE, adverse event; ALSFRS-R, amyotrophic lateral sclerosis functional rating scale-revised; ECG, electrocardiogram; FU, follow-up; MUNE, motor unit number estimation; PK, pharmacokinetic; SAE, serious adverse event. *The precise timing of safety, functional assessments and PK blood sampling may have been altered during the course of the study based on emerging data. If the profile indicated that more sampling or assessments were needed, additional time points were to be added. Study assessments to follow PK sampling at end of infusion. (The 1-hour PK sample was collected directly at the end of the infusion, Cohorts 2–8). †Only SAEs related to study participation were collected prior to the start of the investigational product. Once the investigational product infusion began, all AEs and SAEs were collected until the last FU visit. ‡Continuous Lead II ECG commenced approximately 1 hour pre-dose until 24 hours post-Dose 1 and for 6 hours post-Dose 2. ‡In cohorts 6 and 7 the pre-dose muscle biopsy and blood sample were only done when the subject had passed all screening assessments and eligibility had been reconfirmed. This meant the pre-dose biopsy and blood sample could be done at any appropriate time before Day 1. The post-dose muscle biopsy and blood sample were scheduled for collection at Week 8 (unless emerging data suggested the post-dose muscle biopsy and blood sample should have been collected at an alternative week). In cohort 8, muscle biopsies and blood sample were collected from subjects at pre-dose and at one time point after the first dose.
Subjects were assigned for a post-dose muscle biopsy and blood sample collection at either Day 1 (±24 hours), Day 8 or Week 4 (Day 22–24) based on subject preference determined at screening (see Section 7.3). If the subject had the Day 1 (±24 hours) collection then the pre-dose muscle biopsy and blood sample were collected at least 6 days before Day 1. 4 The number and schedule of FU visits after Week 16 for each subject varied depending on plasma concentrations of ozanezumab reaching a low enough level to allow a final blood sample to have been taken for immunogenicity assays.

Table S3 Primer and probe sets used in biomarker analyses.

Table S4 Summary of Qtc values of potential clinical importance at any visit post-baseline. n, number of subjects; SD, single dose; RD, repeated dose. 2 Two doses, received 4 weeks apart.

Table S5 Summary of ALSFRS-R and MMT analyses. n, number of evaluable subjects; RD, repeat dose; SD, single dose; SE, standard error. ALSFRS-R, ALS functional rating scale-revised; CI, confidence interval; MMT, manual muscle strength test; Measured at Week 12 for SD study, Week 16 for RD study. 2 Two doses, received 4 weeks apart.

Table S6 Summary of SVC and MUNE analyses. CI, confidence interval; MUNE, motor unit number estimation; n, number of evaluable subjects; RD, repeat dose; SD, single dose; SE, standard error; SMUP, single motor unit potential; SVC, slow inspiratory vital capacity. Measured at Week 12 for SD study, Week 16 for RD study. 2 Two doses, received 4 weeks apart.

Methods S1

Results S1

Checklist S1 CONSORT checklist.

Protocol S1 Redacted protocol.

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Conceived and designed the experiments: VM P-FP JP SB NW AC JW BRB JEM BA AB. Performed the experiments: VM P-FP AC GP BRB JBC DL TM SM KEM. Contributed reagents/materials/analysis tools: NW JB AB BK SA-S. Performed the statistical analyses: BA. Undertook data cleaning: NW JB AB. Undertook a literature search: BA. Undertook data cleaning: NW. Provided pharmacokinetic analysis: NW JBC AB. Undertook data analysis interpretation: BV. Responsible for recruitment of patients: P-FP BRB KEM. Undertook a literature search: BA. Undertook data cleaning: NW. Provided immunohistochemistry and laser scanning cytometry analysis: DK. Provided histological examination and histochemical and immunohistochemistry assessment of muscle biopsies: SA-S.

References


