Profile of alglucosidase alfa in the treatment of Pompe disease: safety, efficacy, and patient acceptability

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Abstract: Pompe disease, also referred to as glycogenosis type II, is a rare, autosomal recessive disorder that results from the deficiency of the glycogen-degrading enzyme acid α-glucosidase. The classical form presents shortly after birth with muscle hypotonia, cardiac, and respiratory failure resulting in a fatal outcome. The late onset of Pompe disease has a very variable onset and disease presentation that often causes a delayed diagnosis. Until now enzyme replacement therapy with alglucosidase alfa is the only causative therapy option for Pompe patients that can slow down disease progression. However, uncertainty remains about the efficacy regarding survival and quality of life in Pompe patients under this very cost-intensive treatment. This paper provides a systematic review of the literature stressing different aspects of enzyme replacement therapy in infantile and late onset Pompe patients.

Keywords: lysosomal storage disease, glycogenosis type II, acid maltase deficiency, IOPD, LOPD, enzyme replacement therapy

Introduction

Pompe disease was first described in 1932 by the Dutch pathologist JC Pompe. It is also known as glycogen storage disease type II or acid α-glucosidase deficiency. This orphan disease (OMIM 232300) has an overall incidence which ranges from 1 in 33,000 persons to 1 in 300,000 persons, depending on the geographic region and ethnicity.1–3 Approximately 5,000–10,000 people worldwide are affected. Pathogenetically, the disease is caused by mutations in the GAA gene on the cytogenetic location 17q25.3 (OMIM 606800), resulting in a deficient activity of the enzyme α-1,4-glucosidase that is located in cellular lysosomes involved in the degradation of glycogen. Deposition of lysosomal glycogen takes place in cardiac, skeletal, and respiratory muscle tissue, but also in smooth muscle of the bladder, intestine, esophagus,4 and also the arrector pili muscles of the skin.5 Pompe disease is classified into two clinical forms: The classic infantile onset Pompe disease (IOPD) is related to complete α-glucosidase deficiency that results in a severe disease with onset within the first 6 months after birth. The non-classic form is usually related to partial enzyme deficiency and progresses more slowly with disease onset at any age. It can be sub-categorized as non-classic childhood, juvenile, and adult form (late onset Pompe disease, LOPD).6 Because of the systemic character, clinical features are multiform (Table 1). Cardiomyopathy with heart failure and respiratory insufficiency are the reason for a median age of death between 6 and 9 months in untreated infants7 and a survival rate of 25.7% for the first 12 months.8 In the non-classic form, a progressive limb girdle muscular weakness is the hallmark of the disease, but the broad spectrum of clinical presentations often delays the correct
diagnosis in the patients by an average of 5–8.6 years after the first symptoms.9,10 A decline in the pulmonary function is the main cause of death in this form.11–13 Besides the clinical assessment, other diagnostic clues for Pompe disease include the recognition of a myopathic pattern or myotonic discharges without clinical myotonia14,15 in the electromyography (EMG). Muscle magnetic resonance imaging (MRI), or even better whole body MRI, is more sensitive in detecting subclinical affected muscles and in selecting an appropriate location for muscle biopsy.16 Histologically, Pompe disease presents as vacuolar myopathy in the light microscopy (Figure 1). Vacuoles have a high content of glycogen detected by periodic acid Schiff reaction and are strongly reacting for acid phosphatase, indicating that they are secondary lysosomes.17 It is important to keep in mind that in less severely affected muscles, the vacuoles only show in 25%–75%, and clinically unaffected muscle can be spared from pathological changes, especially in the adult disease.18 A relatively reliable tool for screening for acid α-glucosidase (GAA) deficiency is the assay in blood collected on a filter paper (dried blood spot [DBS]).19 High-throughput mass spectrometry methods are used for the implementation of newborn screening for lysosomal storage disorders (including Pompe disease) in pilot studies in Taiwan, North America, and Europe.20–23 Currently, the “gold standard” diagnostic for Pompe disease is the GAA assay performed on skin fibroblasts or muscle biopsy followed by DNA analysis with detection of homozygote or compound heterozygote mutations in the GAA gene.24,25 To date more than 300 different mutations have been found,26 without strict genotype–phenotype correlation.27

<p>| Table 1 Clinical features of classic and non-classic Pompe patients |</p>
<table>
<thead>
<tr>
<th>Organ system</th>
<th>Symptoms of Pompe disease</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skeletal muscle</td>
<td>Classic form: Floppy infant, delayed motor milestones Non-classic form: Proximal muscle weakness (limb girdle) Exercise intolerance Axial weakness, rigid spine “Dropped head” Rare: IBM-like phenotype Preclinical, isolated hyper-CK-emia</td>
</tr>
<tr>
<td>Pulmonary function</td>
<td>Respiratory failure/hypoxia Respiratory infections Diaphragmatic weakness Exertional dyspnea Hypercapnia Sleep apnea</td>
</tr>
<tr>
<td>Heart</td>
<td>Classic form: Cardiomyopathy, cardiac insufficiency Short PR interval, high QRS voltage One infant case of Wolff–Parkinson–White syndrome Non-classic form: Rare cardiac involvement One adult case of Wolff–Parkinson–White syndrome</td>
</tr>
<tr>
<td>Skeletal system</td>
<td>Scoliosis Osteoporosis Fractures Feet deformities, contractures</td>
</tr>
<tr>
<td>Other organs</td>
<td>Classic form: hepatomegaly Non-classic form: hepatomegaly only reported in the childhood and juvenile onset Pompe disease, not in adults Macroglossia Gastrointestinal symptoms Hearing loss Artheriopathy (aneurysms) Rare: tongue weakness Oropharyngeal dysphagia Posis</td>
</tr>
<tr>
<td>CNS/PNS</td>
<td>Cognitive impairment Rare: small fibre neuropathy</td>
</tr>
</tbody>
</table>

Abbreviations: CK, creatine kinase; CNS, central nervous system; PNS, peripheral nervous system.

Figure 1 Histological findings in Pompe disease.

Notes: Muscle biopsy sections of a patient with genetically confirmed Pompe disease presenting as vacuolar myopathy in H&E staining (A). Elevated lysosomal activity is marked by acid phosphatase reaction (B) in the numerous vacuoles that are loaded with glycogen detected by periodic acid Schiff (PAS) stain (C). Magnification 200×.

Abbreviation: H&E, hematoxylin and eosin.

Enzyme replacement therapy with alglucosidase alfa

The basis for the use of enzyme replacement therapy (ERT) in Pompe disease was built by positive results of intravenously injected precursor forms of recombinant human
α-glucosidase (rhGAA) in the Japanese acid maltase-deficient quail that led to reversal of glycogen accumulation in muscle cells.\textsuperscript{28} Later similar effects were observed with rhGAA in a GAA-knockout mouse model.\textsuperscript{29} Subsequently, pilot Phase I/II studies of rhGAA from purified Chinese hamster ovarian cell culture\textsuperscript{30} or transgenic rabbit milk\textsuperscript{31} significantly prolonged the survival of patients. Since 2006 alglucosidase alfa derived from Chinese hamster ovarian cells (Myozyme®, Lumizyme®; Genzyme Corporation, a Sanofi Company, Cambridge MA, USA) is used for ERT.\textsuperscript{17,32}

**ERT in classical form**

Multiple studies have demonstrated the impressive effect of ERT for improving the survival in classic-infantile Pompe patients (Table 2). An open-label, multinational, multi-center Phase II study demonstrated safety and efficacy of rhGAA in treatment of infantile onset Pompe disease. While untreated IOPD patients die at a median age of 8.7 months, under ERT the 3-year mortality risk is reduced by 95% compared to the natural course.\textsuperscript{7,33,34} Especially, the cardiovascular system responds quickly and strikingly to ERT with a significant reversal of cardiac hypertrophy.\textsuperscript{34–36} However, application of ERT is not a cure but has changed the face of the disease burden from mortality to morbidity. The longer lifespan of infants, who would have died untreated of progressive cardiac involvement, results in manifestation of a more protracted course of muscle weakness, motor speech deficits, sensori-neural and/or conductive hearing loss, osteopenia, gastroesophageal reflux, and dysphagia with aspiration risk and respiratory complications.\textsuperscript{37} Early treatment before development of clinically noticeable motor weakness appears to have the best results for development of the infants. Therefore, newborn screening, as it is practiced in Taiwan, might further render the prognosis positive in IOPD in the future.\textsuperscript{38}

**Antibody formation**

Long-term efficacy and safety of ERT in classic-infantile Pompe disease is strongly dependent on antibody formation against alglucosidase alfa (anti-rhGAA-IgG). Pompe patients without any synthesis of GAA protein are labeled as negative for cross-reacting immunological material (CRIM negative). Kishnani et al demonstrated that CRIM negative patients experienced an initial response to ERT, but then entered a phase of devastating clinical decline comparable to the rate observed in untreated infantile patients. After 2 years of ERT, 11/11 CRIM negative patients were deceased or on invasive ventilation support in contrast to only 4/21 CRIM positive patients.\textsuperscript{39} CRIM negative patients had earlier, higher, and
more sustained antibody responses that were associated with a reduced clinical outcome. CRIM positive patients, on the opposite, have detectable amounts of GAA protein, although its function is insufficient or ineffective. These patients are less prone to immune reactions against rhGAA with usually low antibody titer and typically a better clinical outcome.\(^\text{40}\) However, high doses of therapeutic rhGAA (20–40 mg/kg once a week to biweekly application) can also trigger an immune reaction against ERT in species with only mild mutation of GAA.\(^\text{41}\) Immunomodulatory therapy is a therapeutic approach to reduce the impact of neutralizing antibodies. Combination of rituximab, methotrexate, and intravenous immunoglobulin\(^\text{42–44}\) and also additional treatment with bortezomib, targeting plasma B-cells, successfully reduced antibody titer in infantile Pompe patients and resulted in concomitant sustained clinical improvement.\(^\text{45}\) Importantly, success to induce immune tolerance toward ERT is more likely when immune modulation is started at the onset off ERT.\(^\text{46}\) Therefore, the evaluation of CRIM-negative patients with subsequent immune modulation is important for optimizing benefit from ERT in these patients. In approximately 90% CRIM status can be predicted by mutation type in the corresponding GAA gene.\(^\text{47}\) In uncertain cases, Western blot analysis can be applied for the final CRIM status determination.\(^\text{46}\)

Cost effectiveness and quality of life

Besides the question of therapeutic effectiveness, there is also rising interest in the cost effectiveness of ERT in Pompe disease, especially in the face of tensed health care budgets. In 2014, Kanters et al assessed this topic by a patient simulation model that compared costs, survival, quality of life, and quality-adjusted life years in classic-infantile Pompe disease under ERT and untreated patients. Due to the prolonged survival of treated patients, lifetime incremental quality-adjusted life years were 6.8 with incremental costs-per-life-year-gained estimated to be €0.5 million, of which 95% consisted of treatment costs.\(^\text{48}\)

### ERT in non-classic form

In contrast to the substantial effect of ERT for survival in the classic Pompe disease, the data of ERT in LOPD patients are more variable. Only one randomized placebo-controlled trial in the LOPD exists, which is the basis for approval of reimbursement in the treatment of LOPD.\(^\text{49}\) Since then there have been numerous case reports and observation studies emphasizing the benefit of ERT in non-classic Pompe disease, even though results are not as convincing as in classic Pompe patients (Table 3). Güngör et al demonstrated the positive effect of ERT for survival in 202 ERT-treated versus 81 untreated adults during a median follow-up of 6 years. In all, 28 (61%) of the 46 deaths occurred in the non-ERT-group at a median age of 59.\(^\text{50}\) A review of all studies until January 2012 evaluated effectiveness of ERT in 368 patients. It was shown that at least a stabilization of motor and respiratory function was achieved in most patients. Newer studies support the hypothesis that ERT can extend the time until wheelchair or ventilator dependence. Nevertheless, no clear correlation between length of treatment and clinical improvement could be found.\(^\text{51}\) In contrast, ERT in the British cohort of

### Table 3 Efficacy of ERT in non-classic Pompe disease – study summary

<table>
<thead>
<tr>
<th>Year of study</th>
<th>Total number of participants</th>
<th>Motor performance (6MWT) (n)</th>
<th>Respiration, FVC, FEV₁ (n)</th>
<th>Ventilation (n)</th>
<th>AE (n)</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 2012</td>
<td>368</td>
<td>(122) 77.9%/8.2%/13.9% N/K</td>
<td>(124) 51.5%/13.7%/34.7% Stable</td>
<td>N/K (25) 8 NIV reduced</td>
<td>(303) 30</td>
<td>Toscano and Schoser(^\text{51})</td>
</tr>
<tr>
<td>2012</td>
<td>69</td>
<td>N/K</td>
<td>(62) Stable</td>
<td>1 NIV stopped</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14 NIV stable</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 NIV intensified</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 NIV started</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6 NIV stable</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 NIV started</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>6</td>
<td>N/K</td>
<td>(6) 50%/0%/50%</td>
<td>(69) 12 N/K</td>
<td>de Vries et al(^\text{52})</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>1</td>
<td>Stable</td>
<td>Improved</td>
<td>Stable</td>
<td>None</td>
<td>Iayama et al(^\text{53})</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>(4) 50%/50%/0%</td>
<td>(4) 50%/0%/50%</td>
<td>N/K</td>
<td>N/K</td>
<td>Andreassen et al(^\text{54})</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>(8) 87%/12.5%/0%</td>
<td>(8) Stable</td>
<td>2 NIV reduced</td>
<td>N/K</td>
<td>Deroma et al(^\text{55})</td>
</tr>
<tr>
<td></td>
<td>59</td>
<td>(20) Improved</td>
<td>(N/K) Stable</td>
<td>2 NIV reduced</td>
<td>(8) 1</td>
<td>Anderson et al(^\text{56})</td>
</tr>
<tr>
<td>2015</td>
<td>14</td>
<td>(12) 58.3%/8.3%/33.3%</td>
<td>(12) 16.6%/25%/58.3%</td>
<td>N/K</td>
<td>None</td>
<td>Montagnese et al(^\text{57})</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>(5) 20%/60%/20%</td>
<td>(5) 20%/60%/20%</td>
<td>4 NIV stable</td>
<td>(5) 2</td>
<td>Park et al(^\text{58})</td>
</tr>
</tbody>
</table>

**Abbreviations:** AE, adverse events; ERT, enzyme replacement therapy; FVC, forced vital capacity; FEV₁, forced expiratory volume in 1 second; 6MWT, 6-Minute Walk Test; NIV, non-invasive ventilation; N/K, not known; n, number of participants for which results were available.
The research article discusses the profile of alglucosidase alfa in the treatment of Pompe disease, focusing on antibody formation in non-classic Pompe disease and the effectiveness of enzyme replacement therapy (ERT) in reducing disease progression. The article highlights that approximately one-third of patients do not respond to therapy. The reasons for this inefficacy are explored, particularly in relation to antibody formation against the enzyme alglucosidase alfa. The study of antibody formation is crucial for understanding the therapeutic potential of ERT in Pompe disease.

Key findings include:
- Antibodies against alglucosidase alfa (anti-rhGAA) can occur even after several years of ERT.
- The development of muscle and respiratory symptoms after an asymptomatic period suggests a possible role for anti-rhGAA antibodies.
- A correlation between anti-rhGAA IgG titer and clinical outcomes is observed.
- Generally, females seem to benefit more from ERT than males.

Safety of ERT is discussed, emphasizing its unusual tolerability by patients, with infusion-associated reactions being the most reported adverse events. Steroids or anti-histaminic treatment may be necessary to prevent severe reactions.

Other therapeutic strategies include efforts to further improve the efficacy of ERT. Insufficient rhGAA muscle uptake is likely due to sub-optimal levels of mannose-6-phosphate (M6P), a carbohydrate that binds CI-MPR at the cell surface, resulting in enzyme internalization and lysosomal targeting. Therefore, the design of novel, so-called next-generation forms of ERT is considered promising.

A table lists adverse events (AE) and severe adverse events (SAE) reported under ERT, highlighting the importance of monitoring and managing these events to ensure patient safety.

Quality of life is assessed through the Medical Outcomes Survey Short Form-36 Health Survey (SF-36), which can be divided further into a mental and a physical component score. The international Pompe survey revealed that in 210 untreated adult Pompe patients, the QoL was lower in almost all SF-36 domains relative to the general population. Interestingly, a longer disease duration was associated with a better score in the “role functioning physical” and “mental health” domains, most likely due to coping mechanisms. The 10-year international follow-up data suggest a positive effect of ERT on QoL and on participation in daily life activities in adults by prolonging the natural course of the disease decline. However, only 8.3% of 156 patients under ERT reported an overall improvement in the QoL-scores in contrast to the objective physical improvement of motor and respiratory performance.

Table 4 details adverse events (AE) and severe adverse events (SAE) reported under ERT.

Table 4: Adverse events (AE) and severe adverse events (SAE) reported under ERT

<table>
<thead>
<tr>
<th>AE</th>
<th>SAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infusion-associated reactions:</td>
<td>Anaphylactic reaction45</td>
</tr>
<tr>
<td>Erythema, exanthema, itch, pruritus</td>
<td>Cardiac arrest</td>
</tr>
<tr>
<td>Flushing</td>
<td>Bronchospasm111</td>
</tr>
<tr>
<td>Tachycardia</td>
<td>Severe emphysema and pneumothorax112</td>
</tr>
<tr>
<td>Chest discomfort</td>
<td>Severe tracheal hemorrhage113</td>
</tr>
<tr>
<td>Hypertension</td>
<td>Serious pneumothorax114</td>
</tr>
<tr>
<td>Reduced oxygen saturation</td>
<td>Severe tongue edema112</td>
</tr>
<tr>
<td>Globus pharyngis</td>
<td>Acute hearing loss115</td>
</tr>
<tr>
<td>Vomiting</td>
<td></td>
</tr>
<tr>
<td>Flu-like symptoms</td>
<td></td>
</tr>
<tr>
<td>Pyrexia, chills</td>
<td></td>
</tr>
<tr>
<td>Hyperhidrosis</td>
<td></td>
</tr>
<tr>
<td>Muscle cramps</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviation: ERT, enzyme replacement therapy.
rhGAA with optimized muscle uptake is in progress. Results are awaited for a completed Phase I study known as NEO1 and an ongoing extension study (NEO-ext), evaluating the safety and efficacy of neoGAA with improvement of the CI-MPR-dependent muscle uptake in adults with LOPD.66 In 2010, BioMarin (BioMarin Pharmaceutical, San Rafael, CA, USA; ClinicalTrials.gov identifier: NCT01230801) started clinical studies with GAA ligated with insulin-like growth factor 2 (BMN 701), which allows the enzyme to attach to the surface of the muscle cell more tightly than the normal acid α-glucosidase. Others aim to design ERT with a significantly higher M6P content compared to the alglucosidase alfa (ATB200).68 Enzyme enhancers might also increase the CI-MPR expression and thereby improved rhGAA uptake as it was successfully achieved by the selective β₂ agonists Albuterol in GAA−/− mice, as well as in humans.69 Notably, Albuterol-reduced muscular glycogen even independently from receptor-mediated GAA uptake in the murine model.70 Another strategy is the use of small molecules known as pharmacological chaperones, which bind to the mutant enzyme and recover its lysosomal activity by correcting the protein folding.71,72 However, the presence of a misfolded enzyme with recoverable function is essential for an effect of this class of drug. A potential candidate for pharmacological chaperone therapy is the imino sugar N-butyldeoxynojirimycin, which was shown to increase more than 1.85-fold in α-glucosidase activities in 11 of 13 patients treated with ERT in combination with this chaperone.73 Promising future therapies also involve injection of recombinant adeno-associated virus vectors, as this therapy has been demonstrated to augment cardiac, respiratory, and motoneuron function in GAA−/− knockout mice.74–78 Importantly, the degree of restoration once again seems to depend on the severity of disease. Therefore, an early therapy appears to be the most effective.79 First clinical trials of gene transfer treatment in five ventilator-dependent Pompe patients demonstrated acceptable safety outcomes and longer periods of unassisted breathing.80,81 Genome editing via CRISPR/Cas9 is another revolutionary approach that might tremendously change the therapeutic options for Pompe patients by modulating disease-causing alleles. However, this approach is yet far away from clinical trials.

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