

# The PICO Study: Impact of Phenylalanine on Cognitive, Cerebral and Neurometabolic Parameters in Adult Patients with Phenylketonuria – a Randomized, Placebo-Controlled, Crossover, Non-inferiority Trial

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## Study protocol

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# Abstract

**Background** The population of adult patients with early-treated phenylketonuria (PKU) following newborn screening is growing substantially. The ideal target range of blood Phe levels in adults outside pregnancy is discussed controversially. Therefore, prospective intervention studies are needed to evaluate the effects of an elevated Phe concentration on cognition and structural, functional and neurometabolic parameters of the brain. **Methods** The PICO (Phenylalanine and Its Impact on Cognition) Study evaluates the effect of a 4-week phenylalanine (Phe) load on cognition and cerebral parameters in 30 adults with early-treated PKU in a double-blind, randomized, placebo-controlled, crossover, non-inferiority trial. The primary objective of the PICO Study is to prospectively assess whether a temporarily elevated Phe level influences cognitive performance in adults with early-treated PKU. As secondary objective, the PICO Study will elucidate cerebral and neurometabolic mechanisms, which accompany changes in Phe concentration using advanced neuroimaging methods. In addition to the intervention study, cognition, structural and functional parameters of the brain of adult patients with early-treated PKU will be cross-sectionally compared to healthy controls, who will be comparable with regard to age, gender and education level. Advanced MR-techniques will be used to investigate intensity of neural activation during the working memory task (fMRI), strength of functional connectivity between brain regions related to performance in working memory (rsfMRI), white matter integrity (DTI), cerebral blood flow (ASL) and brain Phe concentrations (MRS). **Discussion** Using a combination of neuropsychological and neuroimaging data, the PICO study will considerably contribute to improve the currently insufficient level of evidence on how adult patients with early-treated PKU should be managed.

## Background

Phenylketonuria (PKU) is a rare autosomal recessive disorder caused by a defective function of the phenylalanine hydroxylase enzyme leading to an impaired conversion of the amino acid phenylalanine (Phe) to tyrosine. Untreated PKU with increased Phe concentrations in blood and brain during childhood leads to severe irreversible neurological impairment with, e.g., mental retardation, intellectual disability, behavioral problems, or other neurological features such as epilepsy or movement disorders. Newborn screening for PKU was established around 1965 rendering possible early treatment with a dietary restriction of Phe (low protein diet) and Phe-free protein substitutes (amino acid mixtures) initiated soon after birth. As a consequence, the population of adults with phenylketonuria with an absence of neurological disabilities is growing substantially since the early 1980s. The majority of these early-treated adult patients live a «normal life» as shown in an earlier study at our center, in which 15 % of the adult patients with PKU went to high school or graduated from university (1).

While there is wide agreement on the treatment strategy and target Phe concentrations in childhood and for women during pregnancy, no consensus on the safe Phe concentrations in adulthood has been reached so far. Traditionally, the low protein diet had been enforced only during childhood and adolescence, leaving adult patients with PKU «off-diet». Nonetheless, there remain concerns that high phenylalanine levels may still have negative effects in adolescents and adults with PKU. There is limited

evidence of irreversible neurological damage, but over the last decade, observational and cross-sectional studies associated high Phe in early-treated adult patients with cognitive problems, psychiatric symptoms and behavioral abnormalities (2–9).

Several studies indicated that even early-treated patients suffer from a variety of mild cognitive impairments. The executive deficit hypothesis of PKU suggests that selective impairments of executive functions may result from abnormalities of neurotransmitters, in particular dopamine, a neurochemical that is critical for prefrontal cortical functions (10). Coming along with alterations of prefrontal cortex functions is a slight decrease in intelligence observed in patients with PKU (11). Decreased intelligence is linked with impairments in higher-order cognitive functions, including executive functions (12) and attention (13). In particular, various studies have reported impaired working memory performance in patients with PKU (11–12). Working memory is an executive function that encompasses the ability of maintaining information during a short period of time, as well as manipulating and refreshing this information to successfully complete a task (16). Hence, working memory is crucial in everyday life, e.g. helping to focus on a demanding task or following a sequence of actions (17). Also other subtypes of executive functions have been reported to be affected from PKU, such as inhibition and cognitive flexibility (12). Most previous studies, however, have focused on selected cognitive functions resulting in a lack of a comprehensive overview across cognitive domains. Such an overview is crucial to increase knowledge about the extent to which cognition is affected by PKU. More importantly, it enables a thorough evaluation of PKU treatment success.

The neurotoxicity of Phe during childhood and adolescence is additionally apparent in regard to structural and functional characteristics of the brain. In detail, an estimated 90 % of patients with early-treated PKU display periventricular white matter lesions and reduced white matter integrity likely impeding processing speed, often reported to be reduced in patients with PKU (18,19).

In contrast, little is known about grey matter changes in PKU. Pérez-Dueñas and colleagues (2006) found volumetric reductions in grey matter structures including motor cortex and thalamus (20). However, data were acquired from a mixed sample of early- and late-treated patients, limiting interpretation of findings. Smaller whole brain volume, smaller parietal and occipital cortex but larger volumina of the putamen were described in early-treated patients with PKU (2,21). The latter study included 9 - 33 years old patients, limiting the generalizability of results due to the lack of comparability between children's and adults cognitive and neuroimaging data.

In regard to functional brain networks, atypical brain activation during a working memory task (22) and decreased functional connectivity (3) have been described, likely coming along with cognitive alterations of this vulnerable patient sample. Patients with PKU have additionally been found to display neurometabolic alterations in upfield and downfield spectra, such as a decrease in choline concentration (23) and an increase in cerebral Phe level (24), respectively. Due to the limited amount of neuroimaging studies, still much uncertainty exists about the relationship between Phe concentrations and brain abnormalities in adult patients. Most importantly, these studies are unable to distinguish between past

effects of elevated Phe levels on the brain during childhood and adolescence and a potentially ongoing negative impact in adulthood. Previous intervention studies were mostly open-label, associating higher and lower Phe intake in the diet with cognitive performance (15). However, the perception of the own compliance with dietary recommendations may influence cognitive performance. One small intervention trial investigated the effect of the Phe concentration on cognition in a prospective randomized, placebo-controlled, double-blinded way. Ten Hoedt and colleagues suggested a negative effect of high plasma Phe levels on sustained attention and on mood in nine adult patients with PKU, concluding that «a Phe-restricted diet for life might be an advisable option for many» (25).

Due to the availability of only low-grade evidence, recommendations of national and international guidelines differ substantially with regard to Phe target levels in adult patients with PKU (26,27). The most recent European guidelines suggest to keep Phe concentrations below 600  $\mu\text{mol/l}$  throughout adulthood while stating this to be a grade D recommendation. Consequently, the recommendations are not only unequally accepted by the treating metabolic specialists, more than 50 % of adults with PKU exhibit substantial difficulty in maintaining the compliance necessary to reach the recommended target Phe concentrations (28,29). Therefore, prospective intervention studies in adult patients with PKU are needed to evaluate the effects of dietary restrictions on cognition, other cerebral and neurometabolic parameters, and quality of life.

## **Objectives**

The primary objective is to prospectively assess the impact of higher Phe load on cognitive performance in adults with early-treated PKU. Secondly, the study aims to elucidate functional and neurometabolic mechanism in the brain accompanying changes in Phe concentration.

## **Methods**

### **Design**

The PICO study is a prospective, single-center, double-blind, randomized, placebo-controlled, crossover, non-inferiority study. In total, 30 adult patients with PKU will be included in the study. PKU patients will crossover, thereby serving as their own controls. To cross-sectionally compare cognitive and neuroimaging data, 30 healthy controls serve as a reference group.

This study protocol is written according to the SPIRIT 2013 Statement (30). providing evidence-based recommendations for the minimum content of a clinical trial protocol. SPIRIT is widely endorsed as an international standard for trial protocols. A SPIRIT Figure is presented below (Table 1).

## **Recruitment**

Patients will be screened in the course of one of their regular metabolic consultations (T0). In addition, patients will be recruited from other adult metabolic centers in Switzerland, e.g. the University Hospital of Zurich. Patients overseen at metabolic centers other than the study site will first be informed about the study by their treating metabolic specialist. Thereafter, patients will be invited by the investigators on condition that they are likely to fulfill the eligibility criteria.

Patients will be asked whether family members or friends are interested in participating in the study as control participants. Healthy controls will be additionally recruited through advertisements placed at websites, word-of-mouth and flyers in the area of Bern.

Interested potential participants will be informed about the study by means of an information brochure and written informed consent will be obtained after the participants had enough time to consider the information and to ask any question.

## **Participants**

30 adult patients with early-treated PKU and 30 healthy controls comparable to patients with regard to age, sex and educational level will be recruited. Patients are eligible for the study if they are age  $\geq 18$  years and have PKU diagnosed after a positive newborn screening and treated with Phe-restricted diet starting within the first 30 days of life.

Patients will be excluded if they did not follow a Phe-restricted diet within 6 months before the study, exhibited Phe concentrations above 1600  $\mu\text{mol/L}$  within 6 months before the study or have a concomitant disease status that could significantly affect primary or secondary outcomes (e.g. untreated vitamin B12 deficiency).

Female patients of childbearing potential will be excluded if they are not using and not willing to continue using one (or more) highly efficient method of contraception (Pearl index less than 1) for the entire study duration, are pregnant or intent to get pregnant during the course of the study or who are breast feeding.

Patients and healthy controls will be excluded if they have known or suspected non-compliance, show drug or alcohol abuse, changed medications likely to significantly interfere with cognitive functions, have known or suspected hypersensitivity or allergy to one of the ingredients of the placebo, are unable to follow the procedures of the study, e.g. due to language problems (lack of fluency in German or French), participated in another intervention study within the 30 days preceding and during the present study, or have a condition that interferes with the safe acquisition of MRI scans.

## **Intervention**

The intervention, consisting of a 4-week oral administration of Phe or placebo in patients with PKU, is initiated to simulate a controlled, temporary discontinuation of their diet. To ensure the blinded setting and avoid changing the usual low protein diet of the patients, Phe or placebo will be administered in form of capsules. In other words, this mimics a Phe-restricted and a Phe-unrestricted diet using a double-blinded, placebo-controlled approach. Patients will be randomly assigned to one of two treatment groups starting either with Phe-containing capsules or with placebo-containing capsules. After 4 weeks, patients cross over to the alternative treatment arm. All patients and study investigators will be blinded to treatment assignment until the completion of the study.

The investigational medicinal product (IMP) consists of capsules containing 500 mg Phe and Placebo capsules indistinguishable from Phe capsules and will be supplied by the Laboratorium Dr. G. Bichsel AG, 3800 Unterseen, Switzerland, according to applicable regulations. The amino acid Phe is part of the normal dietary protein and marketed as a dietary supplement, although not designated for this patient group. Using a similar approach as ten Hoedt (25), the amount of Phe (and placebo) given will be adapted according to sex and body weight with the aim to mimic the total Phe intake likely to be consumed by a healthy adult of the same sex and weight or by the patient with PKU being fully «off diet». Taking into account that the usual daily protein intake in adults in Switzerland is about 0.9–1.2 g per kilogram body weight (31), that the average protein intake is somewhat higher in men than in women, that within a normal diet the portion of Phe of the protein content is about 5 %, and that adult patients with mild to classical PKU mostly consume about 40 % of the usual protein intake, the following additional doses of Phe to be administered were calculated:

- Female <60 kg: 1500 mg per day (divided in 3 doses: 500 mg 1–1–1–0), ≥60 kg: 2000 mg per day (divided in 3 doses: 500 mg 1–1–2–0)
- Male <60 kg: 2500 mg per day (divided in 3 doses: 500 mg 2–1–2–0), ≥60 kg: 3000 mg per day (divided in 3 doses: 500 mg 2–2–2–0)

Assignment to individual doses will be done at the first assessment (T1) after body weight measurement. The assigned dose of the IMP will be kept throughout the whole study and weight fluctuations will not be considered. The capsules can be ingested before, during or after a meal or together with the usual amino acid supplements. The last capsule of the given intervention period will be timed to be ingested with the last meal before the study visit.

In order to prevent the occurrence of carryover effects, a washout period of four weeks has been incorporated in the study design and will be implemented in between the two IMP phases (see Figure 1). The bioavailability of Phe is close to 100 % (32). Phe blood concentrations are known to decrease within one to two weeks after Phe intake reduction in Phe tolerance reassessment (33). The 4-week washout period is equivalent to 12 times the length of the estimated half-life of Phe concentration in the blood of patients with 0 % residual phenylalanine hydroxylase activity (34).

Patients will be asked to maintain their usual protein-restricted diet and amino acid supplements throughout the whole study period. In addition, patients will provide a dietary protocol during the last three days before the first (T1), second (T2), third (T3) and fourth (T4) assessment. They will be instructed to replicate the diet of the three days before T1 as closely as possible during the three days before T2, T3 and T4.

Healthy controls will not receive any intervention but will undergo the same cognitive assessment and neuroimaging measurements as patients at T1 except for blood and dry blood sampling. Healthy controls will only be assessed once (T1).

## **Randomization**

Central randomization will be used to assign participants to the different trial arms with age (< 30 years, > 31 years), sex and center (Zurich, Bern) serving as stratification factors. Randomization lists will be generated by an independent statistician at the Clinical Trial Unit (CTU) Bern. All trial personnel but the statistician generating the list and the personnel at the facility preparing the IMP packs are blinded to the assigned treatment.

## **Investigations**

All study visits and investigations will be performed at the study site, Inselspital, Bern University Hospital, Switzerland. In patients, cognitive performance as well as structural, functional and neurometabolic parameters of the brain will be measured at 4 timepoints, one baseline measurement before each and one measurement after each IMP phase.

T1, T2, T3 and T4 will last about 4 hours and consist of a pregnancy test, fasting blood sample (amino acid profile), neuroimaging, cognitive assessment, physical examination, and assessment of adverse events. Cognitive assessment could be affected by drawing attention to negative influences immediately beforehand. Therefore, physical examination and assessment of symptoms and adverse effects will be placed at the end of each study visit after completion of neuroimaging and cognitive assessment.

The visits will take place in the morning. Before T2 and T4, the last IMP will be taken together with the last meal, which will be placed to approach an antecedent fasting period of 10 hours (range 8–12 hours) before the assessment. For a given patient, T2, T3 and T4 will be scheduled for the same time of the day as the assessment at T1 and the length of the antecedent fasting period will be kept consistent.

## ***Neuroimaging***

*Structural Imaging:* Anatomical MRI will be used to determine structural characteristics of the brain. All MRI images will be acquired using a 3 Tesla Siemens Magnetom Prisma, VE11C Scanner (Siemens Erlangen, Germany), equipped with a 64-channel head coil. Anatomical imaging will be performed using a 3-D T1 magnetization prepared rapid gradient echo (MPRAGE) sequence for acquisition of T1-weighted structural brain imaging (acquisition time TA: 4:33min, repetition time TR=1950ms, echo time TE=2.19ms, slices per slab 176, field of view FoV 256, 1mm voxel resolution).

### ***Functional Imaging:***

Resting state fMRI (rs-fMRI) will be performed to obtain information about regional interactions (functional connectivity) between and within brain regions at rest. For the investigation of rs-fMRI, a multi-band EPI sequence from the University of Minnesota (Center for Magnetic Resonance Research), TA: 5:06min, distance factor 0% (gap 0mm), excitation pulse duration 5120 us, flip angle 30° (avoiding rf-clipping; is in the order of the Ernst angle for TR=300ms and T1 of grey matter) will be used.

Functional MRI (fMRI) of working memory will be assessed to observe the influence of Phe on the characteristics of this higher-level cognitive network. fMRI will be administered using an established paradigm assessing the visuospatial working memory network.

Diffusion tensor imaging (DTI) will be performed to measure the integrity of white matter tracts. For the examination of fractional anisotropy (structural connectivity), a diffusion sequence (MDDW) with 12 directions, slice and PE acceleration 2 and 2 resp., voxel size 2.2mm iso, slices 54, TA: 1:37min will be used.

Three-dimensional arterial spin labeling (3D-ASL) will be applied to assess cerebral blood flow. An QII FAIR 3D-ASL (arterial spin labeling) will be administered (TA: 4:59min PM: REF Voxel size: 1.5×1.5×3.0 mm, slices per slab 40, TR=4600ms, TE=16.18 ms, post-labeling (inversion time) varies depending on patient and age, bolus duration 700ms, inversion time 1500-2000ms). For quantification purpose of arterial blood flow, a M0 run is added. To minimize head motion, a head support system consisting of two pillows positioned on each side of the head will be used. Earplugs will reduce the scanner noise.

Magnetic resonance spectroscopy (MRS) will be utilized to capture potential alterations of brain Phe concentrations. For quantification of MRS-spectra a beta version of the jMRUI-plugin named "spectrlm-QMRS" will be used ([www.jmui.eu](http://www.jmui.eu)) (35).

All MR scans will be subjected to a radiological evaluation by an experienced neuroradiologist

### ***Neuropsychology***

The neuropsychological assessment will include evaluations of general intellectual performance (Wechsler Abbreviated Scale of Intelligence, WASI-II (36)), executive functions (N-Back (Test of Attentional

Performance, TAP (37)); Color-Word Interference Test, Design Fluency (Delis-Kaplan Executive Function System, D-KEFS (38)); Digit Symbol (Wechsler Adult Intelligence Scale Fourth Edition, WAIS-IV (39)), attention (Alertness, Sustained Attention, Divided Attention; TAP (37)), verbal fluency (D-KEFS (38)), processing speed (Digit Symbol, WAIS-IV (39); TMT-A; Color-Word Interference Test, D-KEFS (38)), and fine motor control (Purdue Pegboard (40)). Psychological questionnaires will be used to assess mood (short form of the Profile of Mood States (POMS (41))), depressive symptoms (Beck's Depression Inventory (BDI-II (42))) and health-related quality of life (PKU quality of life (PKUQOL (43))).

### **Primary outcome and hypothesis**

The main hypothesis is that in adult patients with early-treated PKU, a 4-week period of Phe load does not decrease working memory performance measured using accuracy in the visual n-back task of the computerized test of attentional performance (TAP) (37).

### **Secondary outcomes**

The study aims to assess the influence of a 4-week period of Phe load on working memory performance (reaction time, visual n-back task, TAP (37)), inhibition (third condition, color word interference test, D-KEFS (38)), cognitive flexibility (fourth condition, color word interference test, D-KEFS (35)), intensity of neural activation during a working memory test in the MR scanner (n-back task), strength of functional connectivity between brain regions related to working memory (resting-state fMRI), and on brain Phe concentrations (MRS).

### **Other outcomes**

The PICO study will further investigate the influence of a 4-week period of Phe load on cognitive performance, specifically on sustained and divided attention, fine motor control, verbal and design fluency, processing speed, mood (short form of the Profile of Mood States (POMS (41))), Beck's Depression Inventory (BDI-II (42)), and health-related quality of life (PKU quality of life (PKUQOL (43))). Additionally, the influence of temporarily elevated Phe concentrations on integrity of white matter tracts (DTI) and cerebral blood flow (ASL) will be investigated.

Moreover, the study assesses differences between patients with early-treated PKU and healthy controls in regard to cognitive variables, intensity of neural activation during the working memory task, strength of connectivity between brain regions involved in working memory and structural brain characteristics.

## Statistical analysis

The calculation of the sample size is based on the primary outcome (accuracy, visual n-back task of the TAP) for the intra-individual comparison within the different groups using a crossover design. The power analysis was done using Stata based on a paired means test. A non-inferiority margin of 4 % in the n-back task is regarded as clinically irrelevant. According to Zimmermann & Fimm (2009), the test-retest reliability of the n-back task is 0.67 (37). The correlation between two periods will be lower. Therefore, a correlation of 0.5 was assumed for this sample size calculation. Based on reported standard deviations ranging from 5 % to 8 % (15), a standard deviation of 8 % is expected. Based on these assumptions, the PICO study will be able to detect non-inferiority at a margin of 4 %, a power of 80 % and a one-sided alpha level of 0.05 with a sample size of 26 patients. To compensate for possible dropouts, the goal has been set to 30 patients. Additionally, the effect size that would be detectable at different sample sizes and correlations for the comparison of the healthy control group and the experimental group (assuming the same number of controls and patients) was assessed. With a sample size of twice 26 participants and a power of 80 %, an effect size of 0.79 could be detected at a two-sided alpha level of 0.05. To match the number of patients, the goal has been set to 30 controls.

Data will be analyzed according to the intention-to-treat (ITT) principle whereby all randomized participants will be analyzed in the randomized group regardless of any protocol violations. Moreover, data will be analyzed in the per-protocol patient set, excluding patients that did not receive the randomized treatment schedule, patients that did not comply with the intervention, or patients that violated major eligibility criteria.

The primary analysis will be performed in the randomized patient group. As recommended by the CONSORT statement for non-inferiority trials (44), the analysis of the primary outcome will be based on the ITT as well as per-protocol patient set. Raw data of the n-back task will be transformed into standardized values using age matched normative data from the test manual. Normality of data will be assessed via graphical representation of data. Linear mixed effects models will be used to calculate the lower one-sided 95 % confidence limit of the primary outcome. If the lower limit lies above the non-inferiority margin of 4 % in both analysis sets, non-inferiority will be claimed. The mixed effects model will contain the baseline measurements, the 4 weeks measurements, and an indicator for the treatment and period as fixed effects, and a random effect for participants. All primary and secondary continuous endpoints will be analyzed via this approach. Secondary outcomes will primarily be analyzed in the ITT patient set. Secondary outcomes will additionally be evaluated in the per-protocol patient set. Furthermore, processed neuroimaging data will be compared in a cross-sectional and longitudinal manner. Due to the expected heterogeneity of the patient sample, comparisons will be focused on intra-individual changes of cerebral metabolism and functional integrity (comparison Phe vs placebo). Differences between groups will be investigated by linear mixed models, as described above. For the comparison of baseline values between patients and controls, regular linear regression models adjusted for potential confounders will be used.

There is one interim analysis planned for the re-assessment of the sample size. There is currently no reliable data on the correlation between the baseline and 4-weeks measurement and between the two different treatment periods for the n-back test. Therefore, the sample size will be re-assessed after 50 % of patients to assure sufficient power. The re-assessment of the sample size will only be based on the observed standard deviations and correlations between baseline and follow-up values and between treatment periods. Observed changes within and between treatment periods will not be displayed, nor will the non-inferiority margin be modified. No formal testing will take place; therefore, the alpha-level does not require adjustment.

Simple descriptive statistics will be used for evaluation of questionnaires on adverse events and mood. No formal statistical testing will be performed.

## **Data management**

The case report forms (CRFs) in this trial are implemented electronically using a dedicated electronic data capturing (EDC) system (REDCap™, <https://www.project-redcap.org/>). The EDC system is activated for the trial only after successfully passing a formal test procedure. All data entered in the CRFs are stored on a Linux sever in a dedicated mySQL database. Responsibility for hosting the EDC system and the database lies with CTU Bern.

## **Monitoring**

On-site as well as central data monitoring will be part of the quality control activities implemented for this study. Monitoring will be performed according to a separate monitoring plan in collaboration with CTU Bern.

## **Discussion**

The PICO study will help to provide some of the much-needed answers as to if a rigorous protein-restricted diet to control Phe-levels is indispensable to adhere to for adults with early-treated PKU. Using a combination of neuropsychological and neuroimaging data, the PICO study will considerably contribute to an improvement of the currently insufficient level of evidence on how adult patients with early-treated PKU should be managed.

The double-blind, placebo-controlled design will eliminate the expectation bias of patients and physicians otherwise inherent to dietary interventions. Potentially positive effects of the recommended dietary restrictions have to be proven by means of double-blinded intervention trials and not only deduced from biased open interventions and association studies. This is particularly important in light of the potential risks of a lifelong low-protein diet. Similar to a strict vegan diet, a Phe-restricted diet offers not only a lack

in proteins, but also in many micronutrients, both of which have to be monitored and compensated with supplements (45). In addition, the restrictive diets may be associated with a predisposition or aggravation of psychiatric problems in patients with PKU by itself: Eating disorders and obsessive compulsive disorder are four times more common compared to the general population and twice as common as in patients with diabetes mellitus (46).

During the intervention phase, transient mild cognitive impairments might occur due to an increased Phe load. A similar smaller study with increased Phe load over 4 weeks suggested an impairment in sustained attention as well as lower scores in mood profile, but did not report any other mild or serious adverse events (25). Serious side effects are not to be expected. Neither is hyperphenylalaninemia in adulthood known as a cause of metabolic encephalopathy, nor is there a recognized acute decompensation of PKU (47). The probability of irreversible adverse events during the progress of the present study is therefore extremely low. Even in adult patients with PKU not following any low protein diet for a long time, only very few cases of serious neurologic events with unlikely causal relationship (some of them probably caused by severe vitamin B12 deficiency) have been described in the literature up to date: 11 cases of spastic paraparesis, 3 cases of muscle weakness / difficulty walking, 3 cases of vision loss (48). Despite not following any low protein diet for a long time, the majority of adult patients showed improved scores for attention as well as self-reported anxiety and depression after reintroducing a low-protein diet (49,50).

Neuroimaging has become an indispensable tool to better understand brain regions of susceptibility in metabolic disease and to assess the efficacy of dietary treatment on the brain. Clinicians can benefit from the technologic advancements in neuroimaging, allowing for improved understanding of disease and ameliorated patient management. Only a limited amount of neuroimaging studies has been conducted so far in patients with PKU. This is evident on a cross-sectional, but even more on a longitudinal level. Hence, conclusive evidence on the influence of Phe on brain structure and function is not available with the current state of knowledge. By combining a broad range of advanced MR-techniques, the PICO Study strives to advance our understanding of the disease PKU and its impact on different properties of the brain. The additional information gained by the neuroimaging results may help to characterize subgroups of patients that benefit or do not benefit from restrictive dietary interventions.

Evaluation of patients' perceived cognitive performance is an important part of routine patient care (27). However, patients' report may be prone to a substantial expectation bias as they are usually aware of their recent compliance with dietary restrictions. This double-blinded trial offers a unique opportunity to evaluate the reliability of self-assessment of adult patients with early-treated PKU.

The PICO study also yields an economical point of view. Phe-restricted diet, including the use of amino acid supplements and low-protein medical foods, costs about 20'000 CHF / USD per year and patient. Saproprotein (Kuvan<sup>®</sup>), which can be used in the small subset of patients with BH4-responsive PKU, costs about 180'000 CHF / USD annually. Also pegvaliase (Palynziq<sup>®</sup>), the new enzyme substitution therapy (51–53), is estimated to cost about 190'000 CHF / USD per year and patient. Of note, neither saproprotein nor pegvaliase enabled clinically relevant significant improvement of cognitive outcome (19,22,54,55).

Two limitations of the study inherent to the design need to be mentioned. First, being «off-diet» is mimicked, not conducted. Second, the duration of the intervention does not reflect an indefinite discontinuation of the Phe-restricted diet, and long-term effects of elevated Phe levels still remain largely unknown. The oldest early-treated PKU patients are now only in their early 50s. This is a strong argument for keeping all patients with PKU under periodic review and making sure that even those who have stopped dietary treatment are not lost to follow-up. Carefully conducted long-term cohort studies are needed to learn more about the course of the disease as patients age. Based on the current state-of-the-art, patients and their metabolic specialists are unlikely to agree into a longer intervention. A confirmation of the hypothesized non-inferiority could justify a larger long-term trial and support the willingness of patients and treating metabolic specialists to participate in such a long-term trial.

In summary, this randomized, placebo-controlled, crossover, non-inferiority trial using a combination of cognitive and neuroimaging data, will considerably contribute to improve the currently insufficient level of evidence on how adult patients with early-treated PKU should be managed.

## **Trial Status**

The study was reviewed by the Clinical Trial Unit, Bern and the ethics committee of the canton Bern, Switzerland. The manuscript includes all revisions. Recruitment will start in July 2019 and will end in June 2021.

## **Abbreviations**

3D-ASL	3-Dimensional Arterial Spin Labeling
ASL	Arterial Spin Labeling
BDI-II	Beck's Depression Inventory II
CRF	Case Report Form
D-KEFS	Delis–Kaplan Executive Function System
DTI	Diffusion Tensor Imaging
EDC	Electronic Data Capturing
EPI	Echo-Planar Imaging
fMRI	Functional Magnetic Resonance Imaging
GM	Grey Matter
HRQoL	Health-Related Quality of Life
IMP	Investigational Medicinal Product
ITT	Intention to treat
MRI	Magnetic Resonance Imaging
MRS	Magnetic Resonance Spectroscopy
Phe	Phenylalanine
PKU	Phenylketonuria
PKUQOL	Phenylketonuria Quality Of Life questionnaire
POMS	Profile of Mood States
rsfMRI	Resting-state functional MRI
T	Timepoint
TAP	Test of Attentional Performance
WAIS-IV	Wechsler Adult Intelligence Scale Fourth Edition
WASH-II	Wechsler Abbreviated Scale of Intelligence Second Edition

## Declarations

Ethics approval and consent to participate

The research project has been approved by the ethics committee of the canton of Bern, Switzerland (KEK BE 2018-01609). Important study protocol modifications will be reported to relevant parties. In addition, the research project is registered at in online platforms ([www.clinicaltrial.gov](http://www.clinicaltrial.gov) and [kofam.ch](http://kofam.ch)).

After verifying that participants are eligible for the study, the participants and their parents will receive adequate verbal information about the study. They will be given enough time to consider their participation and the informed consent information will be sent to them. Written informed consent will be obtained of all participants. Participants can withdraw from participating at any time, without giving reason for it. If participants discontinue, their data will still be analyzed. Individual medical information obtained as a result of this study is considered confidential and disclosure to third parties is prohibited. Participants' confidentiality will be further ensured by utilizing subject identification code numbers (both on paper and electronically) to correspond to treatment data in the computer files. The key (i.e. a list in which an alphanumeric code is linked to individual participants' names) will be kept separately from the study data in a secured (locked) document. Access to documents, datasets, statistical codes, etc. during and after the study will only be granted to the PI and his designees (e.g., co-authors of the study protocol). The results of the present study will be submitted for publication in peer-reviewed journals and will be presented at national and international scientific meetings to healthcare professionals and/or the public.

#### Consent for publication

Not applicable.

#### Availability of data and material

Not applicable.

#### Competing interest

The authors declare that they have no competing interests.

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## Authors' contributions

The original manuscript was drafted by RT and RE. It was critically reviewed and revised by all co-authors. All authors read and approved the final manuscript. Important contribution to this study protocol were provided by each co-author of this study protocol. RT, RM, LB and RE made substantial contributions to the study design. Funding was acquired by the senior author (RE) and the main co-investigator (RT). Assessments will be conducted by RM, SA and LB, scientific assistants and master students. All examiners receive adequate training supervised by RT and RE. Study coordination will be conducted by RT and RE. Medical experts for the patients with PKU are LB and MH. Experts for the neuropsychological assessments are RM, SA and RE. Experts for neuroimaging are RM, SA, JS, CR and RE.

All authors read and approved the final manuscript.

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## Tables

**Table 1. Schedule of enrolment, interventions, and assessment (according to the SPIRIT guidelines)**

	STUDY PERIOD						
	Recruit- ment	Alloca- tion	Run- in	Study Phase			
				$t_1$	$t_2$	$t_3$	$t_4$
TIMEPOINT	$-t_1$	0					
<b>ENROLMENT</b>							
Eligibility screen	X						
Informed consent	X						
Medical history	X						
Allocation		X					
Dietary Protocol			X				
Distribution of IMP				X		X	
<b>INTERVENTIONS</b>							
Phase 1							
Wash-out							
Phase 2							
<b>ASSESSMENTS</b>							
Baseline variables: <b>Center, sex, age, educational level</b>	X	X					
Blood samples				X	X	X	X
Adverse Events				X*	X*	X*	X*
Outcome variables: <b>Executive functions and fMRI<sup>1</sup></b>				X	X	X	X
Other variables: <b>Physical examination, Cognition<sup>2</sup>, MRI<sup>3</sup>, blood Phe-level, Quality of Life, Mood</b>				X	X	X	X

IMP = Investigational Medical Product

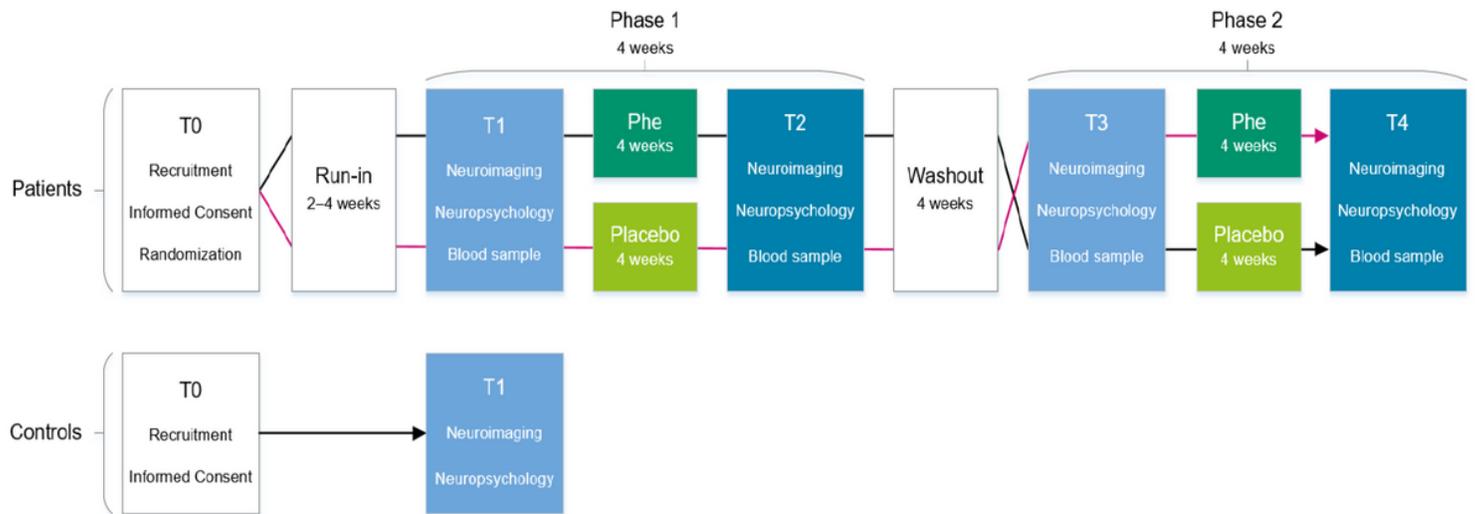
\*additionally weekly phone-calls to assess adverse events

<sup>1</sup> Working memory, inhibition, cognitive flexibility, neural activation during working memory fMRI

<sup>2</sup> IQ, memory, fine motor speed

<sup>3</sup> Voxel based morphometry, diffusion tensor maging, resting-state functional imaging, arterial spin labeling, magnetic resonance spectroscopy

## Figures



**Figure 1**

Study flow chart Legend. T0 = screening; T1 = first assessment; T2 = second assessment; T3 = third assessment; T4 = fourth and last assessment

## Supplementary Files

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