Randomised controlled trial of tyrosine supplementation on neuropsychological performance in phenylketonuria

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Abstract

Objective—To test the efficacy of tyrosine supplementation, as an adjunct to dietary treatment, on neuropsychological test performance in individuals with phenylketonuria.

Design—A randomised controlled trial of tyrosine supplementation using a double blind crossover procedure with three four week phases.

Setting—The Hospital for Sick Children, Toronto.

Participants—21 individuals with phenylketonuria (ages 6 to 28 years, mean 11.3).

Intervention—Participants were given 100 mg/kg body weight/d of L-tyrosine or L-alanine (placebo).

Results—At baseline, performance on several of the neuropsychological test measures was correlated with tyrosine levels. Dietary supplements of tyrosine increased plasma tyrosine concentrations; however, no change in test performance was found across the tyrosine and placebo phases of the study.

Conclusions—Tyrosine supplementation of this type does not appear to alter neuropsychological performance in individuals with phenylketonuria.

(Arch Dis Child 1998;78:116–121)

Keywords: phenylketonuria; tyrosine; phenylalanine; frontal lobe function

When dietary phenylalanine restriction is instituted early in infancy, individuals with phenylketonuria develop with normal intelligence.27 None the less, they have been found to have specific behavioural and cognitive deficits that persist into adulthood, and discontinuation of treatment may result in deterioration in neuropsychological performance.4-17 At least part of these deficits may be reversible by changes in dietary phenylalanine levels. Using crossover designs with periods of high and low phenylalanine intake, Krause et al8 and Clarke et al18 explored the short term neurotoxic effects of hyperphenylalaninaemia on performance on choice reaction time tasks, showing a negative correlation between plasma phenylalanine level and reaction time. Furthermore, Clarke et al found a highly significant improvement in reaction time during the low phenylalanine phase.

Taken together, these observations suggest that at least some component of the neurotoxicity of hyperphenylalaninaemia is reversible by dietary phenylalanine restriction. The mechanism of this late, apparently reversible neurotoxicity is not known; however, it may involve neurotransmitter metabolism resulting from subtle unrecognised nutritional deficiencies. The enzymatic conversion of phenylalanine to tyrosine and the hydroxylation of tyrosine to form dihydroxyphenylalanine (dopa) are impaired by high phenylalanine concentrations.16 The transport of phenylalanine into brain is mediated by a carrier mechanism shared with other neutral amino acids,17 18 and phenylalanine inhibits their transport in vitro.19 20 Plasma phenylalanine concentrations commonly observed in patients with untreated phenylketonuria have been shown to impair the uptake by the brain of other neutral amino acids, including tyrosine and tryptophan, although more recent studies have shown that this effect is not as prominent as the effect on leucine transport into the brain.21 High phenylalanine concentrations also result in sequestration of tyrosine in parenchymal tissue, such as liver.21

Tyrosine is a precursor of the neurotransmitters dopamine and noradrenaline, and tryptophan is the precursor of serotonin. In phenylketonuria, the concentrations of tyrosine and tryptophan in plasma and in brain are below normal.24 25 Krause et al found that urinary dopamine excretion was inversely related to plasma phenylalanine in young adults with phenylketonuria.17 Lou et al reported that cerebrospinal fluid (CSF) concentrations of the dopamine and serotonin metabolites, HVA and 5-HIAA, respectively, were markedly decreased in phenylketonic subjects when they became hyperphenylalaninaemic on unrestricted diets.26 Interestingly, despite marked increases in plasma phenylalanine concentrations, there was no consistent change in CSF tyrosine or tryptophan in their subjects.

Bessman first suggested that low brain tyrosine might be as critical as high phenylalanine in the damage caused to phenylketonuric patients.27 Studies testing that hypothesis have yielded mixed results. Lou et al showed increased neurotransmitter biosynthesis in two patients with phenylketonuria on supplementation with large doses of tryptophan (100 mg/kg) and tyrosine (200 mg/kg), and in addition found improved reaction times in the one patient who had abnormal vigilance.26 Lou et al28 and Lykkelund et al29 studied patients with phenylketonuria who were allowed unre-
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Methods

SUBJECTS

Twenty-three individuals with phenylketonuria (12 females, 11 males) were recruited from the phenylketonuria clinic of the Hospital for Sick Children in Toronto. All subjects spoke English as a first language, were in good health, and were not taking any psychoactive drugs. Two subjects (both male) were not included in the final analyses: one admitted that he had not been taking his supplements consistently during the study, and one was not shifted from tyrosine to the placebo at a planned phase change, because of a pharmacy error.

The mean age of the final sample of 21 subjects was 11.3 years (SD 6.2; range 6 to 28), and their mean full scale intelligence quotient (IQ) (based on the age appropriate form of the Wechsler intelligence scale) was 102 (SD 11.2, range 82 to 123). All patients were on phenylalanine restricted diets, although in two cases the restriction was minimal. The intake of tyrosine in the amino acid supplements given as part of the dietary treatment was highly variable, with a maximum of 100-150 mg/kg body weight. At baseline, the mean plasma phenylalanine concentration was 785.3 µmol/l (SD 202.7, range 472 to 1148 µmol/l), and the mean plasma tyrosine concentration was 41.6 µmol/l (SD 12.1; range 24 to 67 µmol/l).

MATERIALS AND PROCEDURE

The following tasks were administered in the baseline and three supplementation phases: two tests of choice reaction time (simple and vigilance reaction time tasks), a test of response organisation and monitoring (self ordered pointing task), two tests of response inhibition (delay task and conflicting motor task), and a task requiring short term memory with or without distraction. Choice reaction time tasks have been shown to be sensitive to dietary phenylalanine, to dietary levels of tyrosine, to CSF HVA and 5-HIAA levels, and to plasma phenylalanine concentration. The remaining tasks tap abilities that have been shown to be sensitive to the effects of frontal lobe damage in adults, and have also been used in developmental studies on frontal lobe functioning. A word list memory task and a measure of receptive vocabulary were included as control tasks; alternate forms of these two tests were administered at baseline and at the end of the second supplementation phases only. A detailed description of the tasks is presented in the appendix.

All aspects of the study were conducted on an outpatient basis. A double blind crossover within subject study design was employed. All subjects were maintained on therapeutic low phenylalanine diets throughout the study. The dietary supplements consisted of an “anonymous” powder, which was either L-tyrosine (100 mg/kg/day) or the placebo, L-alanine (100 mg/kg/day). Alanine was selected as a placebo because it is relatively tasteless compared with other amino acids, and it is harmless, being rapidly oxidised or converted to glucose.

The daily dose of powder was divided into two portions, to be taken in the morning and the afternoon, mixed in food. Two randomisations of three phases were used, either TAT or ATA, where T refers to the tyrosine supplementation phase and A to the alanine, or placebo, phase. Subjects underwent baseline neuropsychological and biochemical testing,
and were then randomly assigned to an initial A or T phase. The assignment of subjects to the initial phase, and the dispensing of the powders, was done by a research pharmacist. The tyrosine supplementation status of the subjects was concealed from all others (the subjects, their parents, the physicians caring for the subjects, and the neuropsychologist) until the end of the study.

Each phase lasted four weeks. Neuropsychological and biochemical testing was repeated at the end of each phase. After four weeks on the initial phase (A or T), each subject was tested and changed to the opposite phase (A to T or T to A) for a further four week period; this pattern was repeated for the third phase. In total, each subject underwent testing four times (baseline and at the end of each of the three phases).

Plasma phenylalanine and tyrosine concentrations were monitored by quantitative amino acid analysis performed by automated ion exchange chromatography (Beckman Model 7300 amino acid analyser).

**Results**

At baseline, plasma phenylalanine was significantly correlated with the following dependent measures: total words recalled on the word list memory task ($r = -0.73$, $p < 0.01$), number of words recalled in the no distraction version of the short term memory test ($r = -0.75$, $p < 0.05$), number of errors on the self ordered pointing task ($r = 0.51$, $p < 0.05$), and reaction time in the vigilance task ($r = 0.57$, $p < 0.05$). Tyrosine concentrations at baseline were significantly correlated with number correct on the delay task ($r = 0.56$, $p < 0.05$), number of errors on the self ordered pointing task ($r = -0.57$, $p < 0.01$), and the correlation between phenylalanine and tyrosine was not significant ($r = -0.39$, $p > 0.05$).

The results for the supplementation phases were analysed in two ways. First, the results for the subjects randomised to the ATA design and those randomised to the TAT design were analysed separately. In the second set of analyses, to increase statistical power all subjects were pooled and the data were averaged across all tyrosine phases and all non-tyrosine (baseline and placebo) phases. In both analyses, paired $t$ tests were conducted to investigate any changes in the biochemical or neuropsychological variables over time as a function of the supplementation status of the subject. These analyses yielded the same outcome, and thus only the combined subject analyses are reported. Also, no differences were found between subjects undergoing the ATA regimen and those undergoing the TAT regimen.

Mean plasma phenylalanine and tyrosine concentrations across the tyrosine supplementation and non-supplementation phases of the study are reported in table 1. There was no significant change in phenylalanine ($t_{(1,20)} = 0.18$, $p > 0.05$), but tyrosine levels were significantly higher on tyrosine supplementation than on placebo ($t_{(1,20)} = 2.76$, $p < 0.05$). However, the phenylalanine to tyrosine ratio did not vary significantly with the supplementation status of the subjects ($t_{(1,20)} = 1.51$, $p > 0.05$).

Table 2 gives the means and standard deviations for the measures administered across all four phases of the study, and the $r$ values and probabilities associated with the analyses. This table also contains the confidence intervals for the mean differences between the tyrosine and non-supplementation conditions, together with the standard errors for those mean differences. No significant differences were detected in any of the dependent variables.

Because Lou et al found their effect of tyrosine supplementation on reaction time variability, secondary analyses were con-
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cantly correlated, as one might expect if dietary
control totally explained the findings. Second,
the neuropsychological variables which corre-
lated with the plasma biochemical variables dif-
fed for tyrosine and phenylalanine. Again, one
would assume that better dietary control would
lead to lower phenylalanine and higher tyrosine
and thus influence the same tasks. It is therefore
possible that tyrosine may be exerting an inde-
pendent effect. This possibility is supported by
previous findings in patients with atypical phenyl-
ketonuria or mild hyperphenylalaninaemia, in
whom no correlations between phenylalanine
and IQ measures were seen, but in whom
phenylalanine levels correlated significantly with
the performance IQ, which comprises tasks of
nonverbal reasoning and visuomotor functioning.37

In this study, supplementation with tyrosine
in patients with phenylketonuria who were on
low phenylalanine diets resulted in a significant
increase in plasma tyrosine. None the less, this
increase was not associated with any change in
performance, relative to that seen with admin-
istration of a placebo, on reaction time or cog-
nitive tests. Lou et al had originally shown an
effect of tyrosine supplementation on reaction
time variability38; we were unable to replicate
the effect with our measure of reaction time
variability or with any of the other tasks. Thus
our results support the conclusion arising from
other recent studies, that tyrosine supplemen-
tion appears to be of no benefit to individuals
with phenylketonuria, whether or not they are
restricting dietary intake of phenylalanine. This
conclusion appears to apply not only to
performance on neuropsychological measures,
such as demonstrated here and by others,30 31
but also to neurophysiological indices of brain
function, including visual evoked potentials
and EEG.31 Because of recent evidence indicat-
ing that patients with phenylketonuria have
cognitive deficits related to frontal lobe
abnormality,32 34 the test battery used in the
present study had used measures sensitive to
frontal lobe functioning, suggesting that the
negative results were not due to inappropriate
task selection.

In the present study, the dietary supplements
of tyrosine resulted in an average increase in
plasma tyrosine concentrations such that they
were 130% of the baseline value. This increase
is smaller than that reported in other studies.
Pietz et al found tyrosine levels of 200% of
baseline values with the same dose,33 and Lou
reported a mean increase to 276% of baseline
with his higher doses of tyrosine (106–194
mg/kg/day).35 In normal volunteers, a value of
223% of baseline plasma tyrosine concentra-
tions has been demonstrated two to eight hours
after ingesting 100 mg/kg of tyrosine in a single
dose.36 As Pietz et al have suggested, these dif-
fences across studies may be due to the
differences in administration, as for example in
capsule alone or powder mixed with food, or
ingested at one time as opposed to spread out
during the day.

In understanding the consistent failure to
replicate the results reported by Lou and col-
leagues,37 considerations of dosage may be
important. The tyrosine supplement of 200
mg/kg employed by them was at least twice as
high as that used in all subsequent investigations. It may be that the positive results obtained were due to greater availability of tyrosine in the brain to compete with phenylalanine for transport across the blood–brain barrier. This possibility has not been addressed directly in any of the studies reported, and would be difficult to assess in an ethical manner in human subjects.

What is not known in the present study or other recent investigations is the effect of dietary supplementation on brain levels of tyrosine. Of more importance than the plasma tyrosine level itself is the ratio of phenylalanine to tyrosine, since phenylalanine competes with tyrosine for carrier proteins at the blood–brain barrier. Although the dietary supplements increased the amount of tyrosine in plasma, they did not significantly alter the phenylalanine to tyrosine ratio, which was approximately 18:1 when subjects were ingesting tyrosine and 20:1 when they were not. Both of these ratios were well above the normal 1:1 ratio.

Various potential reasons why we failed to find a supplementation effect were considered. One is that the subjects may not have been compliant with ingesting the dietary supplements. Detailed dietary records were kept during the study, and were reviewed by one of the authors (VA), a registered dietitian. With only one exception (whose data were not included in the study), all participants reported being compliant with the supplementation regimen. It is also possible that the clinical heterogeneity of the sample of subjects prevented the expression of treatment effects. There may be a genetic component to endogenous tyrosine levels, or it may be that tyrosine concentrations early in life may influence cognitive development, and there is a critical (early) age after which cognitive development cannot be altered by dietary supplementation, at least at the levels of tyrosine employed in this study. Finally, the four week supplementation period may have been insufficient for possible effects to be seen; this possibility is unlikely, given that Lou et al found an effect after only three days of tyrosine supplementation.

Many centres that follow patients with phenylketonuria have adopted tyrosine supplementation as an adjunct method of treatment. The baseline correlations between tyrosine and task performance suggest that tyrosine availability may play an important part in the neuropsychological performance of patients with phenylketonuria. However, our results show that, although dietary tyrosine supplements increased plasma concentrations of tyrosine, they did not have an effect on neuropsychological test performance under the conditions of our study. The supplementation we employed would not appear to be successful in offsetting the cognitive deficits in phenylketonuria. On the other hand, the findings suggest that further studies are necessary to determine whether alternate methods of administration may be more effective in increasing the availability of tyrosine to the brain.

This research was funded by grants from the Ontario Mental Health Foundation and the Vanier Foundation. We are grateful to all the participants and their families for the time and enthusiasm they dedicated to this project, to Michael Wasdell for assistance with the statistical analyses, to Jennifer Saltzman for editorial assistance, and to anonymous reviewers for their suggestions for improvements to the manuscript.

Appendix
DESCRIPTION OF TASKS
Two reaction time tasks, taken from the Gordon diagnostic system, requires a self contained, electronic testing device, were administered. In the first task, named the reaction task, subjects viewed a random series of numbers from 0 to 9, which appeared for 200 ms every 2 s in the centre of a three column electronic display; subjects were required to respond as quickly as possible by pressing a button whenever a 0 appeared. There was a total of 30 targets. In the vigilance task, based on the continuous performance test, they had to respond only when a 9 appeared which had been preceded by a 1. The digits each appeared for 200 ms at a presentation rate of 1 per second. This task contained 45 targets. Reaction time, number correct, and errors of commission were recorded for each task.

The self ordered pointing task, adapted from Petrides and Milner, requires response organisation, planning, attention, and short term memory. Subjects were presented with stacks of 21.5 × 28 cm pages, each containing a matrix of 6, 8, 10, or 12 pictures of familiar objects. No picture appeared in more than one matrix set. Within a matrix set, the same pictures appeared on each page, but their relative positions on the page varied randomly. Subjects were instructed to touch each picture in the set, by going through the pages one at a time, and touching one picture on each page. Pictures could be touched in any order, but each picture was to be touched only once. Subjects were told not to point to the same spatial location on consecutive pages. Three trials were given for each set of pictures, beginning with the six item set and progressing to the 12 item set. Number of errors was summed across all trials for all sets.

Two measures of response inhibition were used: the delay task and the conflicting motor task. The delay task, also from the Gordon diagnostic system, measures the ability to suppress or delay impulsive behavioural response. The subject was instructed to press a button, wait an unspecified time, and then press the button again. If the subject refrained from responding for at least 6 s, a light flashed and a reward counter incremented. If the subject responded before the interval elapsed, the timer reset and no reward points were obtained. The task yielded two scores: total number of responses and the efficiency ratio, which represents the percentage of correct responses from the total responses.

The conflicting motor response task, adapted from Christensen, required the subject to perform motor actions opposite to that modelled by the examiner. Subjects were trained to make two gestural signals (“Show me your fist,” “Show me your finger”). They were then told that when the examiner showed a fist, they were to show a finger, and that when the exam-
In each of these two gestures was presented 40 times in a predetermined random sequence at a rate of one gesture per second. Number of errors were recorded.

The short term memory task, modelled after work by Brown and Peterson and Peterson, was administered only to subjects 11 years and older. There were two versions of the task, each containing 10 trials of four words which subjects were asked to recall, in the order in which they were presented, after a delay of 20 seconds. In the no distracter version of the task, this delay was left unfilled, whereas in the distracter version, the subject was given a three digit number and was asked to count backwards from that number until the interval had elapsed. The order of presentation of these two versions was counterbalanced. A maximum of eight points per trial was awarded, one point for each word recalled, and one point for the order in which the word was recalled.

In the word list memory task, subjects were read 12 unrelated words (taken from the lists used by Hannay and Levin, over three repeated trials. Recall was tested following each trial, and after a delay of 15 minutes. The dependent variable was the sum of words recalled across the three trials and the delay trial.

In the Peabody Picture Vocabulary Test—Revised, a measure of receptive vocabulary, the subject was shown a series of pictures, four to a page. For each item, the subject was asked to choose the picture that corresponded to a word spoken by the examiner. Number of correct items was converted to a standard score (mean of 100, SD 15) based on norms for the subject’s age.