Plasma guanidino compounds are altered by oral creatine supplementation in healthy humans

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Over the past 10 yr, creatine has become one of the most popular dietary supplements of the Western world. Whereas its use was initially confined to the athletic population, the clinical potential of creatine supplementation is now investigated for a variety of diseases (recently updated in Refs. 8a, 31). Despite the widespread use of oral creatine supplements by athletes and patients, little is known about its impact on the regulation of endogenous creatine synthesis.

Over 50 yr ago, Hoberman et al. (12) showed that creatine chronically inhibits endogenous synthesis at the transamidination step in humans, supporting earlier animal studies showing a powerful repressive effect of creatine on L-arginine:glycine amidinotransferase (AGAT). As shown by Van Pilsum and coworkers (10, 20), this feedback repression by creatine at the rate-limiting step of synthesis probably occurs at the pretranslational level of AGAT expression, rather than by a direct effect on enzymatic activity. This is further supported by the time course of AGAT suppression, which occurs in the range of days or weeks rather than hours (9). To our knowledge, the effect of chronically elevated plasma creatine levels, due to creatine supplementation in humans, on GAA formation has hardly been studied. Over 50 yr ago, Hoberman et al. (12) showed that creatine ingestion in a human subject resulted in elevated GAA excretion (12). This corroborated the prevailing opinion that the methylation of GAA (the second step), rather than its formation (the first step), was rate determining for creatine synthesis (12). However, these data seem more puzzling presently because they could implicate a species difference indicating that creatine synthesis suppression in humans is not exclusively accomplished on AGAT as in rats but that it occurs also at the site of GAMT.

Therefore, in the present study, we have examined the circulating GAA concentrations in humans, sub-pectected to a 1-wk high-dose (20 g) and subsequent 19-wk low-dose (5 g) creatine supplementation protocol. This will allow us to indirectly register whether the transamidinase (decreased GAA levels would indicate AGAT inhibition) or methylation (elevated GAA levels would indicate GAMT inhibition) reaction is the main site of creatine biosynthesis regulation in humans. It could be hypothesized that arginine sparing, by creatine synthesis suppression, may result in upregulation of other...
metabolic fates of arginine, such as formation of urea and ornithine, guanidinosuccinate (22), α-keto-γ-guanidinovaleric acid (GVA), and argininc acid (16). We have therefore investigated a wide range of guanidino compounds, which are related by well-described or less clear links to arginine. Several of the guanidino compounds are epileptogenic and are described as probable neurotoxins in uremic disease (5, 6). Although the moderate use of creatine supplements has no consistently reported adverse effects (23), it remains important to investigate whether creatine supplementation causes elevation of guanidino compound concentrations in the physiological or pathological range, which could yield a topic of interest for the study of potential side effects of prolonged or high-dose creatine supplementation.

METHODS

Subjects. Sixteen young volunteers (age 18.8 ± 0.3 yr, 12 men and 4 women) gave their written, informed consent to participate in the study. The study protocol was approved by the local Ethics Committee (Universitair Ziekenhuis Gasthuisberg, Leuven, Belgium). The subjects reported to not have taken creatine supplements for the 6 mo before the study. They were instructed to abstain from taking any medication and to avoid making any changes in their physical activity level and other living habits during the period of the study.

Study protocol. A double-blind study was performed over a 20-wk period. Before the subjects started the supplementation, baseline measurements were obtained. Then, the subjects were assigned to either the placebo group (Pl; receiving maltodextrine) or to the creatine group (Cr; receiving creatine monohydrate). Subjects ingested 20 g of creatine (divided over 4 portions to be taken at regular intervals throughout the day) or placebo during the first week, and one dose of 5 g in the morning for the following 20 wk. Measurements were performed at baseline, after 1 wk of loading, and after 10 and 20 wk of low-dose supplementation.

Plasma metabolites. Fasting plasma samples were deproteinized by adding an equal volume of a trichloroacetic solution (200 g/l) and subsequent centrifugation in a Beckman microfuge (Beckman Instruments International, Geneva, Switzerland). Two hundred microliters of supernatant were used for guanidino compound determination, using a Biotronic LC 5001 (Biotronik, Maintal, Germany) amino acid analyzer adapted for guanidino compound determination. The guanidino compounds were separated over a cation-exchange column using sodium citrate buffers, and they were detected with the fluorescence ninhydrin method as previously reported in detail (18). Detected compounds include creatine, creatinine, GVA, GAA, guanidinosuccinate, arginine, argininc acid, homoarginine, α-N-acetyl arginine, guanidine, and γ-guanidinobutyric acid. Plasma urea was determined with diacetylmonoxime as described by Ceriotti (3).

Creatine retention. One week before the start of the study and after 1, 10, and 20 wk of supplementation, the supplementation protocol was interrupted for 1 day for determination of creatine retention, where all subjects (Pl and Cr) received a single dose of 10 g of creatine monohydrate. The subjects reported to the laboratory in the morning after an overnight fast, emptied their bladder, and received an oral load of 10 g of creatine monohydrate dissolved in 250 ml of water. Subjects were instructed to collect all urine during the following 24 h. The total urine volume was measured, and the creatine content of an aliquot was determined by a standard enzymatic fluorometric assay. Creatine retention was calculated as the difference between the amounts of creatine ingested (10 g) and excreted over the 24-h period.

Statistical analysis. Statistical comparison between Pl and Cr groups was done by applying a two-way ANOVA for repeated measures with time as within-subject factor and treatment as between-subject factor. Significance was accepted when the P value for interaction between time and treatment was <0.05. Correlations were calculated by means of a product-moment test. All statistical procedures were conducted by using Statistica software (Statsoft, Tulsa, OK).

RESULTS

Plasma guanidino compounds. As shown in Fig. 1A, plasma creatine levels at baseline were 20–30 μM and remained in this range throughout the study in Pl. In Cr, fasting plasma creatine levels were 10-fold higher after the 1-wk high-dose supplementation and remained ~5-fold higher in the 19-wk low-dose regimen. Plasma GAA levels (Fig. 1B) remained at baseline level (± 2.4 μM) in Pl, but they decreased by 50 and 20–30% in Cr after high-dose and low-dose creatine supplementation, respectively (P < 0.05). When all plasma samples of Cr are considered, the GAA levels correlated negatively (R = −0.59;


P < 0.05) with creatine levels (Fig. 1C). Plasma arginine concentrations were ∼80–100 μM and remained unchanged over time (Table 1). At week 20, however, arginine concentrations were significantly different between treatment groups because of a nonsignificant fall and rise in Pl and Cr, respectively.

Table 1 shows the significant effects of creatine supplementation on guanidino compound levels. After 1 wk of supplementation, homocitrulline, GVA, and arginincic acid levels in Cr were increased by 35, 45, and 75%, respectively, compared with baseline (P < 0.05), whereas they remained unchanged in Pl. These changes were not present during subsequent long-term low-dose supplements. Plasma creatinine was slightly increased throughout the study in Cr (Table 1), the difference in significance at 1 and 20 wk. In Cr, guanidinosuccinate concentrations decreased from 290 ± 64 nM at baseline to 214 ± 34 nM after 1 wk (P < 0.05), yet they returned to baseline levels in the subsequent phase of the study. Other plasma guanidino compounds were unaffected by treatment: α-N-acetyl arginine, guanidin, and urea. The concentration of γ-guanidinobutyric acid was below the detection limit in most samples.

Creatine retention. At baseline, 3.7 ± 0.8 and 5.1 ± 0.8 g of creatine were excreted in the 24 h after 8.8 g creatine (10 g creatine monohydrate) ingestion in Pl and Cr (not significant), respectively (Table 2). Creatine excretion remained unchanged in Pl throughout the study and increased (creatine retention decreased) at 1, 10, and 20 wk in Cr.

**DISCUSSION**

A major finding of the present study is that plasma GAA concentration is reduced by exogenous creatine supplementation in healthy humans. GAA is an intermediate between the first and second reaction of creatine biosynthesis, and this suggests that hypercreatinemia suppresses creatine synthesis at the first committed step, catalyzed by AGAT. This finding is in accordance with the findings of several studies performed in animals (10, 20, 28). Although one cannot rule out the possibility that the decrease in circulating GAA levels is caused by alternative mechanisms (excretion, degradation, transport), the negative correlation between plasma creatine and GAA levels (Fig. 1C) demonstrates that creatine is possibly a powerful regulator of AGAT in vivo in humans. However, because the first blood sample was only taken after 1 wk of creatine supplementation, our results do not allow discriminating whether the negative feedback is obtained by rapid catalytic activity inhibition or by reduced enzyme expression. Analogy with animal studies would suggest that the latter phenomenon is predominant because reduction of AGAT activity is observed not within hours but only within days after the start of creatine supplementation (9). Therefore, future studies will have to determine the exact time course of downregulation of creatine biosynthesis in humans. The creatine supplementation regimen employed in the present study (1-wk loading phase with 20 g/day and a subsequent maintenance dose of 5 g/day) is routinely used by athletes and patients, on the basis of scientific evidence (13, 27). We now suggest that such creatine supplementation regimen downregulates endogenous creatine biosynthesis within 1 wk and as long as supplementation is continued.

A second aim of the present study was to explore the impact of creatine supplementation on the circulating levels of related guanidino compounds, assuming that arginine sparing would stimulate alternative pathways of arginine catabolism. Interestingly, several of the metabolites were sensitive to creatine

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**Table 1. Plasma concentrations of the guanidino compounds that were influenced by creatine supplementation**

<table>
<thead>
<tr>
<th>Compound</th>
<th>Baseline</th>
<th>Week 1</th>
<th>Week 10</th>
<th>Week 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homocitrulline, μM</td>
<td>Pl 1.72±0.14</td>
<td>1.89±0.15</td>
<td>1.90±0.18</td>
<td>1.75±0.17</td>
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<tr>
<td></td>
<td>Cr 1.68±0.22</td>
<td>2.27±0.32*</td>
<td>1.58±0.19</td>
<td>1.48±0.11</td>
</tr>
<tr>
<td>a-Keto-g-guanidinvaleriacid, nM</td>
<td>Pl 47.6±3.8</td>
<td>48.6±6.5</td>
<td>ND</td>
<td>51.6±8.3</td>
</tr>
<tr>
<td></td>
<td>Cr 47.4±6.3</td>
<td>69.2±6.5*</td>
<td>ND</td>
<td>49.6±4.12</td>
</tr>
<tr>
<td>Arginincic acid, nM</td>
<td>Pl 94±8</td>
<td>94±8</td>
<td>121±20</td>
<td>98±18</td>
</tr>
<tr>
<td></td>
<td>Cr 89±10</td>
<td>156±18*</td>
<td>110±19</td>
<td>108±16</td>
</tr>
<tr>
<td>Creatinine, μM</td>
<td>Pl 78.4±2.8</td>
<td>79.3±3.3</td>
<td>76.3±2.7</td>
<td>78.6±4.4</td>
</tr>
<tr>
<td></td>
<td>Cr 78.6±3.1</td>
<td>89.4±3.8*</td>
<td>81.7±4.1</td>
<td>89.2±4.5*</td>
</tr>
<tr>
<td>Guanidinosuccinate, nM</td>
<td>Pl 252±21</td>
<td>262±30</td>
<td>278±25</td>
<td>268±19</td>
</tr>
<tr>
<td></td>
<td>Cr 290±64</td>
<td>214±34*</td>
<td>278±58</td>
<td>270±79</td>
</tr>
<tr>
<td>Argininc, μM</td>
<td>Pl 102.9±8.1</td>
<td>105.4±7.7</td>
<td>98.9±6.7</td>
<td>88.8±12.8</td>
</tr>
<tr>
<td></td>
<td>Cr 90.4±8.2</td>
<td>86.7±7.2</td>
<td>89.4±8.5</td>
<td>98.3±9.1*</td>
</tr>
</tbody>
</table>

Values are means ± SE. Pl, placebo group; Cr, creatine-supplemented group; ND, not determined (because of analytic problems). *Significant difference compared with Pl, P < 0.05.
supplementation. Although modest in magnitude, L-homoarginine levels were elevated by 1-wk high-dose creatine supplementation (Table 1). Homoarginine may be formed by a homologous urea cycle (Fig. 2) in which ornithine is replaced by lysine (25). In the light of the possible physiological effects of elevated homoarginine levels by creatine supplementation, it is important to note that homoarginine can replace arginine as a substrate for nitric oxide (NO) synthase in the formation of NO (15).

The present data show that creatine supplementation clearly induces elevated GVA and argininic acid levels. It has been suggested that GVA could be synthesized by transamination from arginine and that it can be further metabolized to argininc acid (4, 16). GVA and argininic acid are metabolically related and are elevated in states of hyperargininemia (19). The present findings suggest for the first time that even in the absence of hyperargininemia, the supposed creatine synthesis suppression can lead to upregulation of a secondary pathway of arginine metabolism, i.e., synthesis of GVA and argininic acid. The latter guanidino compounds are convulsants and can inhibit GABA responses in neurons (7, 8), although it should be emphasized that the concentrations reached in the present study are far below the pathological range. Despite the popularity of creatine as a nutritional supplement for >10 yr, no such side effects on the central nervous system amino acid responses have been reported or suspected. Therefore, it is unlikely that the increased circulating concentrations of GVA and argininic acid are a potential source of harmful side effects at the studied dosage (5–20 g) of creatine supplementation.

Some theories exist about the biosynthesis pathway of guanidinosuccinate, of which the transamidination of arginine to aspartate (22) (theory 1), the transformation of urea to guanidinosuccinate through the so-called “guanidine cycle” (21) (theory 2), and the cleavage of argininosuccinate by the hydroxyl radical (2) (theory 3) received most attention. Although a tight coupling between guanidinosuccinate and urea is well established, the metabolic relationship between arginine and guanidinosuccinate is controversial. Some investigators have shown that increased availability of arginine gives rise to guanidinosuccinate formation through transamidination (22) (theory 1), whereas others believe that arginine, a NO precursor, by elevating NO production, leads to scavenging of the hydroxyl radical, necessary for cleavage of argininosuccinate to guanidinosuccinate (1) and consequently decreased guanidinosuccinate synthesis (theory 3). Our present data show that guanidinosuccinate levels decrease with the increased arginine supply.
availability, which likely results from suppressed creatine synthesis. Thus our data are more in agreement with theory 3 than with theory 1 and 2. Theory 3 suggests that increased arginine availability leads to an inhibition of guanidinosuccinate synthesis from argininosuccinate because increased arginine leads to increased NO production and a lesser availability of hydroxyl radicals necessary for the cleavage of argininosuccinate. A similar pattern of decreased guanidinosuccinate levels and increased GVA and arginine acid levels is present in hyperargininemic patients (17), which further supports the idea that the altered guanidino compound pattern in the present study is secondary to elevated arginine availability.

In Fig. 2, we attempt to summarize the effects of oral creatine supplementation on the metabolic pathways around arginine. Following this proposed scheme, downregulation of AGAT expression stimulates flux through secondary pathways leading to formation of GVA, arginine acid, homoarginine, and possibly NO but not of urea. These effects occur after 1 wk of 20 g/day supplementation but not after 10–20 wk of 5 g/day.

The urinary excretion of creatine and creatinine is shown in Table 2. The total ingested amount of creatine is 8.8 g (by oral challenge) plus a presumed dietary intake of ~0.5–2 g (11) and an unknown amount of endogenously synthesized creatine. Thus, at baseline, a minimum of 9.3 g of creatine is added to the total creatine pool, and between 5.2 g (Pl) and 6.7 g (Cr) are excreted (as creatine and creatinine), leaving a net increase in body creatine content of minimum 2.6 to 4.1 g. After 1, 10, and 20 wk of creatine supplementation, the fractional excretion increased to ~100% of the total amount of dietary creatine, indicating no further increase in and a saturation of the body creatine content. In light of this abundance of body creatine and nearly complete excretion of ingested creatine, the mechanism of downregulation of endogenous creatine synthesis provides a valuable way to spare amino acids and energy in the human body.

In summary, the present results for the first time confirm in humans that oral creatine supplementation in doses of 5–20 g/day is related to a reduction in circulating GAA levels, suggesting that endogenous creatine synthesis is chronically (up to 5 mo) suppressed at the level of the transaminidase reaction catalyzed by AGAT. Additionally, these data suggest that creatine biosynthesis repression leads to enhanced utilization of arginine as a substrate for secondary guanidino compound pathways.

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GRANTS

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