Iron, Copper, Magnesium and Zinc Status as Predictors of Swimming Performance¹,²

H. C. Lukaski, W. A. Siders, B. S. Hoverson, S. K. Gallagher
USDA, ARS Grand Forks Human Nutrition Research Center, Grand Forks, ND, U.S.A.

The hypothesis that blood biochemical measurements of iron (Fe), copper (Cu), magnesium (Mg) and zinc (Zn) nutritional states and dietary intakes of these minerals are useful predictors of 100-yd free-style swimming performance during actual competition was examined in five female and five male collegiate swimmers. Dietary intakes of Fe, Cu, Mg, and Zn exceeded 70% of daily recommended or estimated safe and adequate intakes. Anemia was not present but body iron stores, assessed with serum ferritin concentration, were reduced in female swimmers who had significantly increased erythrocyte Mg and superoxide dismutase activity which suggest a biochemical adaptation to physical training. Actual 100-yd freestyle times (53.1 ± 1.4 sec; mean ± SE) measured during competition were similar to values (52.6 ± 1.4 sec) predicted with models previously derived from other groups of swimmers. These findings indicate the important role of mineral nutritional status in facilitating the development of peak physical performance and support the hypothesis that mineral element nutritional status is one factor contributing to attainment of optimal human physiological function.

Key words: Diet, nutritional status, human performance

Introduction

Trace elements, such as copper (Cu), iron (Fe), magnesium (Mg) and zinc (Zn), are minerals that are required in small quantities (mg) and are necessary for life. Each of these essential nutrients has defined biological functions which have been shown to influence energy utilization and may be hypothesized to impact work performance (13). For example, Cu is an important component of the cytochrome system and is needed for utilization of Fe and protection against oxidative damage (20) which also is regulated by the cytosolic enzyme superoxide dismutase that requires Zn for structural integrity and Cu for enzymatic activity (21). Magnesium, because of its wide distribution in the body, plays a fundamental role in many cellular reactions, including energy transduction (11). Zinc, which is associated with more than 300 enzymes that participate in macronutrient metabolism, is required for the activity of lactate dehydrogenase and carbonic anhydrase that play critical roles in energy metabolism during exercise (6).

Despite this basic knowledge, there is a paucity of information relating mineral element nutritional status to measures of human physical performance. Significant correlations were reported between 100-yd free-style swim times and dietary Zn intake in male swimmers and biochemical measurements of Fe storage and transport in female swimmers (17). In addition, models for the estimation of 100-yd swim performance were developed from determinations of dietary mineral intake and blood biochemical indices of trace element status (17).

The purpose of this study was to compare determinations of 100-yd free-style performance with predictions derived from models based on measurements of trace element nutritional status in a sample of collegiate swimmers. It was hypothesized that the derived models would yield estimates of swimming performance that were similar to the measured swimming performance.

Material and Methods

Subjects

Five female and five male members of the University of North Dakota swim team participated in the study; one of the swimmers was physically challenged with asthma. Although more than 15 swimmers expressed initial interest in participating in

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this study, only 10 swimmers completed all scheduled testing. A medical history and physical examination of each volunteer was completed before admission into the study. This investigation was conducted with the approval of the University of North Dakota Institutional Review Board and the US Department of Agriculture Human Study Committee. Written informed consent was obtained from each volunteer before participation in nutritional status assessment and testing.

Experimental design

This study utilized a cross-validation design. An independent sample of collegiate swimmers was previously recruited for the derivation of models using blood biochemical measurements of mineral nutritional status and estimates of dietary mineral intake to predict 100-yd free-style swim performance during competition in another sample of collegiate swimmers.

Body composition

Standing height, without shoes or socks, was measured to the nearest 0.1 cm with a stadiometer (Harpenden; Pembrookeshire, England) mounted on a wall. Body mass was determined on a calibrated scale (Toledo Scale, model 2831; Worthington, OH) accurate to ±0.2 kg.

Body composition was assessed by hydrodensitometry using the equipment and procedures described by Akers and Buskirk (1) with the modification that the strain gauges were mounted underwater in the tank. Residual lung volume was measured simultaneously during the determination of mass in water by use of an open-circuit technique for nitrogen washout of the lungs (8). Percent body fat was calculated from body density measurements according to Brozek et al. (4).

Dietary intake

Nutrient intakes were estimated during the week before the conference men's and women's swimming championships by using self-reported, 3-d dietary records obtained from the freelifing volunteers who consumed self-selected diets. Food records were reviewed at the end of the 3-d period, which included one day of a weekend, for completeness of food descriptions and amounts of different foods consumed. Questions were asked to identify foods that might have been overlooked. The dietary records were coded for computer calculations by trained clerical staff and checked by a dietitian. The nutrient intakes were calculated by GRAND, a computerized dietary data analysis system based on USDA food composition data (28,29) and trace element data from other published sources (9,12,23).

Biochemical assessments of mineral nutritional parameters

Fasting venous blood samples were obtained during the same period when the dietary records were collected. Standard biochemical analyses were selected to assess trace element nutritional status (10). Measurements of hematocrit and hemoglobin were made with a standard method and instrumentation (Coulter model S; Coulter Electronics, Hialeah, FL). Plasma Cu, Mg and Zn were determined by flame atomic absorption spectrophotometry after dilution with deionized water (22). Whole-blood samples were digested with concentrated nitric acid and 70% perchloric acid then the Cu, Mg and Zn contents of the digestates were determined by using flame atomic absorption spectrophotometry with aqueous calibration standards (18). Plasma Fe and total iron-binding capacity (TIBC) were measured by zeeman graphite furnace atomic absorption spectrometry with prior precipitation by trichloroacetic acid (5). Percent transferrin saturation was calculated from the serum Fe concentration and TIBC (27). Serum ferritin was measured by radioimmunoassay (Baxter Travenol Diagnostic Inc; Cambridge, MA). Superoxide dismutase (SOD) activity was assayed in erythrocytes by the method described by Winterborn et al. (31).

Swim performance

Individual swimmer's times for the completion of the 100-yd freestyle event during the 1993 North Central Conference championships were obtained from the official record of the meet.

Prediction models

Individual 100-yd freestyle times were predicted with the following models derived from another sample of 10 female and 6 male collegiate swimmers (17). Briefly, nutritional status was assessed early and at the end of the competitive season by using 3-d dietary histories and biochemical analyses of venous blood (plasma and red blood cell Cu, Fe, Mg, Zn concentrations, hematocrit, hemoglobin, ferritin, transferrin saturation, enzymatic and immunoreactive ceruloplasmin, and SOD activity) taken after an overnight fast. Swim performance in 100-yd free-style was recorded in competition within one week of the nutritional assessment. Step-wise multiple regression analysis was used to derive a model for the prediction of 100-yd swim performance by sex.

Male swimmers

Time (sec) = 0.49 transferrin (%) - 0.20 Mg intake (mg/1000 kcal-d) + 1.52 Zn intake (mg/d) + 3.61 ln (ferritin, μg/l) - 2.01 Fe intake (mg/1000 kcal) + 2.01 RBC Mg (mmol/l) + 0.001 SOD (U/g Hgb) + 19.58 (R² = 0.951; standard error of the estimate or SEE = 1.2).

Female swimmers

Time (sec) = 1.02 plasma Fe (μmol/l) - 1.40 Zn intake (mg/1000 kcal) - 0.68 transferrin (%) + 10.5 Cu intake (mg/1000 kcal) + 56.56 (R² = 0.93; SEE = 0.8).

Statistical methods

Values are presented as mean±SE. Significant differences between female and male swimmers for physical characteristics, nutritional variables and swim times were determined with the unpaired t-test (25). The paired t-test was used to compare observed and predicted values (25). The relationship between observed and predicted values was determined with linear regression analysis (25). Bias was examined by using the method of Bland and Altman (2). Analysis of variance was used to simultaneously determine if the slope and intercept of the relationship between measured and predicted swim times were similar to the line of identity (25).
Results

Body composition

Standing height (181.2 ± 2.8, mean ± SE, vs 169.7 ± 2.9 cm) and body mass (77.8 ± 1.5 vs 63.9 ± 1.5 kg) were greater (p < 0.01) among the male as compared to the female swimmers. Fat-free mass (68.5 ± 1.4 vs 50.2 ± 1.1 kg) was greater (p < 0.01) but percent body fat (10.9 ± 0.9 vs 15.0 ± 1.0%) was less (p < 0.01) for the male than the female swimmers.

Dietary intake

None of the swimmers reported routine ingestion of nutritional supplements or pharmaceutical intakes than their female team mates (Table 1). Iron, Cu, Mg, and Zn intakes expressed as mg/d also were greater (p < 0.05) for the male swimmers. However, when the mineral intakes were normalized for energy intake (e.g., per 1000 kcal/d), Fe, Cu and Zn intakes were similar between the groups. Magnesium intake on a 1000 kcal basis was greater (p < 0.05) among the female, as compared to the male, swimmers.

Table 1  Estimated dietary intake of the swimmers.

<table>
<thead>
<tr>
<th></th>
<th>Females</th>
<th>Males</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy, kcal/d</td>
<td>2085 ± 130*</td>
<td>3943 ± 132*</td>
</tr>
<tr>
<td>Carbohydrate, g/d</td>
<td>260 ± 22</td>
<td>440 ± 33*</td>
</tr>
<tr>
<td>Protein, g/d</td>
<td>76 ± 5</td>
<td>120 ± 7*</td>
</tr>
<tr>
<td>Fat, g/d</td>
<td>87 ± 3</td>
<td>142 ± 9*</td>
</tr>
<tr>
<td>Iron, mg/d</td>
<td>12.5 ± 1.0</td>
<td>19.2 ± 2.1*</td>
</tr>
<tr>
<td>mg/1000 kcal</td>
<td>5.9 ± 0.4</td>
<td>5.4 ± 0.5</td>
</tr>
<tr>
<td>Copper, mg/d</td>
<td>1.3 ± 0.1</td>
<td>1.8 ± 0.1*</td>
</tr>
<tr>
<td>mg/1000 kcal</td>
<td>0.6 ± 0.04</td>
<td>0.5 ± 0.02</td>
</tr>
<tr>
<td>Magnesium, mg/d</td>
<td>269 ± 25</td>
<td>393 ± 30*</td>
</tr>
<tr>
<td>mg/1000 kcal</td>
<td>125 ± 8</td>
<td>110 ± 5*</td>
</tr>
<tr>
<td>Zinc, mg/d</td>
<td>10.5 ± 0.8</td>
<td>17.6 ± 2.0*</td>
</tr>
<tr>
<td>mg/1000 kcal</td>
<td>4.9 ± 0.2</td>
<td>4.7 ± 0.4</td>
</tr>
</tbody>
</table>

* Values are mean ± SE
  * Significantly different (p < 0.05) than corresponding value for female swimmers

Analyses of the dietary records indicated that the swimmers consumed a conventional diet of western foods. On the average, the energy distribution was 18 ± 2% protein, 61 ± 3% carbohydrate and 21 ± 5% fat. The diet was balanced and contained foods from the major food groups. The major dietary contributors of Fe were meat, poultry, fish, cereals, and vegetables. Nuts, legumes and grain products were the principal sources of dietary Mg. Grain and animal products provided the majority of the dietary Zn. Dietary Cu came from nuts, seeds and grain products.

Blood biochemical assessment of mineral nutritional status

There was no evidence of anemia among any of the swimmers (Table 2). Males had greater (p < 0.05) values for hematocrit and hemoglobin than did the females. Other indices of iron status, serum ferritin, plasma iron and transferrin saturation, also were increased (p < 0.05) in the men. Total iron-binding capacity was similar among both groups of swimmers.

Table 2  Blood biochemical measurements of trace mineral status of the swimmers.

<table>
<thead>
<tr>
<th></th>
<th>Females</th>
<th>Males</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hematocrit, l</td>
<td>0.39 ± 0.01*</td>
<td>0.43 ± 0.01*</td>
</tr>
<tr>
<td>Hemoglobin, g/l</td>
<td>134 ± 2</td>
<td>155 ± 2*</td>
</tr>
<tr>
<td>Ferritin, µg/l</td>
<td>26 ± 5</td>
<td>67 ± 12*</td>
</tr>
<tr>
<td>Iron, µmol/l</td>
<td>18.1 ± 1.2</td>
<td>20.6 ± 1.3*</td>
</tr>
<tr>
<td>TIBC*, µmol/l</td>
<td>62 ± 3</td>
<td>56 ± 2</td>
</tr>
<tr>
<td>Transferrin, %</td>
<td>31 ± 1</td>
<td>37 ± 1*</td>
</tr>
<tr>
<td>Copper, µmol/l</td>
<td>15.9 ± 1.1</td>
<td>13.9 ± 0.6*</td>
</tr>
<tr>
<td>Magnesium, mmol/l</td>
<td>0.85 ± 0.02</td>
<td>0.88 ± 0.02</td>
</tr>
<tr>
<td>Zinc, µmol/l</td>
<td>12.7 ± 0.4</td>
<td>14.6 ± 0.4*</td>
</tr>
<tr>
<td>RBC* Mg, mmol/g Hgb</td>
<td>7.69 ± 0.29</td>
<td>6.25 ± 0.25*</td>
</tr>
<tr>
<td>SOD**, U/g Hgb</td>
<td>5225 ± 124</td>
<td>3359 ± 109*</td>
</tr>
</tbody>
</table>

* Values are mean ± SE
  * Significantly different (p < 0.05) than corresponding value for female swimmers by unpaired t-test
  $ Total iron-binding capacity
  $ Red blood cell
  ** Hemoglobin
  *** Superoxide dismutase

The female swimmers had increased (p < 0.05) plasma copper but decreased (p < 0.05) plasma zinc concentrations as compared to the male swimmers. Plasma magnesium concentration was similar among both groups of swimmers.

Erythrocyte magnesium concentration was assessed; it was greater (p < 0.05) in the female as compared to the male swimmers. Red blood cell superoxide dismutase activity was greater (p < 0.05) in the females than the males.

Swimming performance

Times for the 100-yr free-style swim were greater (p < 0.05) for the female (56 ± 2.0 sec) than the male (50 ± 1.8 sec) swimmers. There was no difference between the times predicted by using the sex-dependent models (52.6 ± 1.4 sec) and the actual swim times (53.1 ± 1.4 sec) for the combined group of swimmers. A comparison of individual observed and predicted swim times is shown in Fig. 1.

The measured and predicted swim times are highly correlated (r = 0.97, p < 0.001). The slope of the line relating the values is similar to 1 and the intercept is not different than 0 (Fig. 2).
The plot of the residual scores (observed - predicted times) indicates no systematic bias in the prediction of 100-ym swim times (Fig. 3).

Discussion

The results of the present study show that 100-ym free-style performance can be accurately predicted with blood biochemical measurements of Fe, Cu, Mg, and Zn nutritional status and estimates of the dietary intake of these minerals. Although a generalized relationship previously has been reported between hemoglobin concentration and measures of human work capacity (30), there have been no attempts to demonstrate the validity or the precision of this model to assess the impact of iron-deficiency anemia on human physical performance.

The hypothesis that indices of trace element nutrure are predictors of human physiologic function emanates from knowledge of the general biochemical functions of these mineral elements. There is general awareness that Fe, Cu, Mg, and Zn play important regulatory roles in intermediary metabolism (11, 13, 16). In addition, reports of the improved physiological function with mineral supplementation indicate a potentially important role of Zn and Mg in physical activities in which glycolytic metabolism is dominant. Krotkiewski et al. (15) found a significant increase in dynamic isokinetic strength and isometric endurance in middle-aged women after short-term Zn supplementation (135 mg/d for 2 wk) in a cross-over design. Because of the critical role of Zn in regulating lactate dehydrogenase activity, Krotkiewski et al. (15) speculated that Zn supplementation improved muscle strength and endurance by affecting muscle metabolism directly.

Beneficial effects of an interaction between Mg supplementation and physical training on strength gain of humans also have been reported. Brilla et al. (3) observed significantly increased torque of quadriceps muscle in Mg-supplemented (507 mg Mg/d or 144% RDA) as compared to placebo-treated (246 mg Mg/d) young men after strength training. The positive effects of Mg supplementation may be related to the regulatory function of Mg on protein synthesis and glycolytic metabolism (11).

Although these findings suggest a propitious role of generalized Zn and Mg supplementation on muscle function, the interpretation of these observations should be tempered with caution. In each of these studies (3, 15), there is a lack of biochemical evidence to demonstrate either a deficiency of the supplemented mineral element or a change in mineral nutrition after supplementation. This evidence is critical in establishing whether the mineral supplement acted as a nutrient, and thus remedied a mild or marginal nutritional deficiency, or functioned as a drug, thereby having a pharmacologic effect which has the potential to promote adverse secondary effects on other minerals (16).

Dietary intake of the trace elements was considered adequate for the swimmers because the estimated intakes were greater than 70% of recommended amounts (26). The female swimmers reported consuming Fe, Mg and Zn intakes that were 83, 96 and 88%, respectively, of amounts recommended for American women. Male swimmers reported intakes that were greater than 100% of recommended intakes. Because the safe and adequate range of Cu intake for adults is designated as 1.5 to 3 mg/d (26), the average estimated copper intake of the female swimmers was less, but the Cu intake of the male swimmers was within this proscribed range. The impact of usual Cu intakes in these amounts is not known because most adults routinely do not consume amounts of dietary Cu in the range of safe and adequate intake (14).

Biochemical assessment of nutritional status of the swimmers provides some important findings. Although anemia was not identified, Fe nutrure was depressed slightly among the female as compared to the male swimmers. None of the values was indicative of Fe deficiency. Serum ferritin concentrations
among the females were consistent with previous findings among female athletes (13); that is, there was a mild reduction in body Fe stores. Indices of transport Fe were similar among both groups of swimmers.

In addition to the slight decrease in serum ferritin, the female swimmers also had another sex-dependent difference in mineral status. Serum Cu concentrations were significantly greater. This finding is consistent with the effect of estrogen on increasing circulating Cu in women during their reproductive years (20).

Erythrocyte Mg concentration and superoxide dismutase activity also were significantly greater in the female swimmers. Because it was previously reported that red blood cell Mg was a significant predictor of peak oxygen uptake (18) and that increased superoxide dismutase activity was a functional adaptation to aerobic training (19), one might speculate that the female swimmers had more competitive swimming performances than their male counterparts. Although the women had slower times than the men in the same event (56 vs 50 sec), more of the women had greater success (e.g., 4 individual championships for the women as compared to 1 for the men). Thus, it may be hypothesized that erythrocyte Mg and superoxide dismutase may be biochemical indicators of training and future performance. However, the limited sample size and the relatively large analytical variability (>10%) of these indices may limit their usefulness.

Biochemical assessment of Cu, Mg and Zn status is limited by the availability of sensitive indicators that reflect subclinical deficiency. In contrast to Fe, for which relatively sensitive measurements of Fe-containing proteins reflect body Fe stores (ferritin) and transport Fe (transferrin), static measures of plasma Cu, Mg and Zn represent a body pool of the mineral that is generally unresponsive to small alterations in body mineral status as might be expected with short-term changes in dietary Cu, Mg and Zn intake (10). Other biochemical markers, such as ceruloplasmin, SOD and erythrocyte Mg, which are considered functional indicators of Cu and Mg nutritional status, are more responsive to alterations in dietary Cu and Mg. The models previously derived in swimmers utilized the functional biochemical variables of ferritin, transferrin, SOD, and erythrocyte Mg, along with dietary Fe, Cu, Mg, and Zn, as predictors of swim performance.

Many factors contribute to maximizing physical performance. A critical component of success is technique or biomechanical function. Other components of performance include psychological inputs, such as motivation and concentration, and biological influences, including body composition and physiological function. Nutritional status, particularly macronutrient (e.g., carbohydrate and water) intake, has been previously emphasized for endurance activities (7). The results of the present study emphasize the importance of trace element nutritional status for activities that have a dominant component of glycolytic metabolism, such as 100-yd free-style swimming.

These findings may be applied to physically active people as well as competitive athletes. Because dietary intake of trace mineral elements is an important predictor of performance, individuals should be aware that consumption of a variety of foods from the major food groups will enhance the potential for receiving adequate amounts of mineral elements in the diet. Individual inquiries for improving food choices to enhance trace element intake should be directed to a licensed dietitian who is experienced with the life-style and demands of physically active people. Use of individual mineral supplements should be discouraged because of well known adverse interactions on mineral absorption (16).

In conclusion, we demonstrated the validity of prediction models based on measurements of trace element nutritional status to estimate 100-yd free-style performance of female and male collegiate swimmers. These findings indicate the importance of mineral elements in optimizing human physical performance and emphasize that adequate amounts of essential minerals can be obtained from a conventional diet.

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