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Selenium Bioavailability from Naturally Produced High-Selenium Peas and Oats in Selenium-Deficient Rats

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ABSTRACT: This study determined the bioavailability of selenium (Se) from yellow peas and oats harvested from the high-Se soil of South Dakota, United States. The Se concentrations were 13.5 ± 0.2 and 2.5 ± 0.1 mg/kg (dry weight) for peas and oats, respectively. Male weanling Sprague−Dawley rats were depleted of Se by feeding them a 30% Torula yeast-based diet (4.1 μg Se/kg) for 56 days, and then they were replenished with Se for an additional 50 days by feeding them the same diet supplemented with 20, 30, or 40 μg Se/kg from peas or oats, respectively. Selenium bioavailability was determined on the basis of the restoration of Se-dependent enzyme activities and tissue Se concentrations in Se-depleted rats, comparing those responses for yellow peas and oats to those for L-selenomethionine (SeMet; used as a reference) by using a slope-ratio method. Dietary supplementation with peas or oats resulted in linear or log−linear, dose-dependent increases in glutathione peroxidase activities in blood and liver and in thioredoxin reductase activity in liver. Supplementation with peas or oats resulted in linear or log−linear, dose-dependent increases in Se concentrations of plasma, liver, gastrocnemius muscle, and kidneys. The overall bioavailability was approximately 88% for Se from yellow peas and 92% from oats, compared to SeMet. It was concluded that Se from naturally produced high-Se yellow peas or oats is highly bioavailable in this model and that these high-Se foods may be a good dietary source of Se.

KEYWORDS: selenium, bioavailability, peas, oats, rats

INTRODUCTION

Selenium (Se) is an essential nutrient for humans and livestock. Its nutritional essentiality was first reported in 1957, when it was shown to prevent diet-induced liver necrosis in laboratory animals.[1] Selenium is an integral part of the catalytic site of several enzymes, including glutathione peroxidase (GPX)[2] and thioredoxin reductase (TRR);[3] the former catalyzes the reduction of hydroperoxides and hydrogen peroxide by reduced glutathione, the latter catalyzes the NADPH-dependent reduction of the redox protein thioredoxin, and both function to protect cells from oxidative damage. An adequate intake of Se prevents Se-deficient diseases in humans[4,5] and livestock,[6] and dietary supplementation with Se is associated with potential health benefits for humans, including an enhancement in immune responses,[7] an improvement of thyroid health,[8] and a reduction in cancer risk.[9]

Selenium from dietary sources can be metabolized through different mechanisms, which determine its functions and destination in the body. There are two major Se compartments, a selenocysteine (SeCys) compartment comprising a relatively small number of proteins containing Se incorporated as SeCys by a highly specific cotranslational process,[10−12] and a nonspecific selenomethionine (SeMet) compartment composed of general proteins in which SeMet is incorporated as a mimic of its sulfur analogue methionine. The SeCys compartment is regulated by the availability of Se at low levels of intake. The SeMet compartment is relatively large, potentially including all sites of methionine in body proteins. The nonspecific incorporation of SeMet is not specifically regulated. Selenomethionine is a dominate form of Se in plant foods,[13−15] which upon its absorption can be nonspecifically incorporated into the SeMet compartment or metabolized via enzymatic or nonenzymatic steps to enter the SeCys compartment or be methylated and excreted in urine. Selenium deficiency affects both compartments with decreases in Se-dependent enzyme activities and depletion in tissue Se, which are responsible for Se-deficient diseases in humans[4,5] and livestock.[6]

The soil Se contents among the agricultural states in the United States vary widely. The states in the Northern Plains, for example, the Dakotas, have sufficient or adequate Se in soil, whereas others are low or marginally deficient in Se.[16,17] The Se concentrations of agricultural crops reflect the Se contents of the producing soils,[18] and those produced in the Northern Plains, for example, wheat[19] and soybeans,[20] are high in Se. Available studies show that Se from high-Se soybean,[20] wheat,[19] and buckwheat [21] are highly bioavailable, suggesting that those foods are a good dietary source of Se. Field peas and oats are among the major crops produced in the Northern Plains, and yellow peas and oats we sampled from South Dakota contained 13.5 and 2.5 mg Se/kg, respectively. The nutritional values of peas and oats have been well documented,[22] and both are commonly used for human food products (e.g., split pea soup and oatmeal) and for animal feed.[23,24] However, potential health benefits of these high-Se foods have not been evaluated. The purpose of the present study was to determine the bioavailability of Se from yellow peas and oats that were naturally produced from the high-Se soil of South Dakota.

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Table 1. Composition of the Basal Diet[a]

ingredient	g/kg
corn starch	427.4
Torula yeast	300.0
sucrose	100.0
soybean oil	70.0
cellulose	50.0
mineral mix[b]	35.0
AIN-93G vitamin mix	10.0
L-methionine	2.9
L-cystine	3.5
L-tryptophan	0.16
choline bitartrate	1.0

[a] At 30% of the diet, Torula yeast[27] provides an adequate amount of all essential amino acids for rodents except cystine (1.8 g/kg), methionine (2.4 g/kg), and tryptophan (1.84 g/kg) according to the NRC recommendations for cystine (4.9 g/kg), methionine (4.9 g/kg), and tryptophan (2.0 g/kg).[28] Thus, these amino acids were added to the diet to meet the recommendations. At 30% of the diet, the yeast provides 0.9 g/kg choline, and we added an additional 0.4 g choline/kg (1.0 g choline bitartrate/kg) to the diet to meet that provided by the AIN-93G formulation.[26]. [b] Mineral mix contained calcium carbonate, anhydrous, 40.04% Ca, 555.26 g/kg; sodium chloride, 39.34% Na, 52.17 g/kg; sodium metasilicate, 9 hydrate, 9.88% Si, 1.45 g/kg; chromium potassium sulfate, 12 hydrate, 10.42% Cr, 0.275 g/kg; copper carbonate, 57.47% Cu, 0.143 g/kg; boric acid, 17.5% B, 0.082 g/kg; sodium fluoride, 45.24% F, 0.064 g/kg; nickel carbonate, 45% Ni, 0.032 g/kg; lithium chloride, 16.38% Li, 0.017 g/kg; potassium iodate, 59.3% I, 0.010 g/kg; ammonium paramolybdate, 4 hydrate, 54.34% Mo, 0.008 g/kg; ammonium vanadate, 43.55% V, 0.007 g/kg; and powdered sucrose, 390.482 g/kg.

MATERIALS AND METHODS

This study was approved by the Animal Care and Use Committee of the USDA−ARS Grand Forks Human Nutrition Research Center. The procedures followed the guidelines of the National Institutes of Health for the care and use of laboratory animals.[25]

Diet Preparation. A 30% Torula yeast-based diet formulated according to the AIN-93G formulation[26] was used as the Se-deficient basal diet, in which the yeast was used as the protein source (Table 1). Torula yeast is relatively rich in Fe, P, K, Zn, Mn, and Mg,[27] and a 30% yeast diet provides adequate amounts of these minerals for rodents. Thus, a mineral mix was prepared containing only those minerals needed to meet the National Research Council (NRC) recommendations[28] and those included in the AIN-93G formulation[26] (Table 1). A Se-adequate diet (positive control) was prepared by adding SeMet to the basal diet to bring the total Se level to 150 μg Se/kg according to the AIN-93G formulation.[26] Cooked, dried powder of yellow peas (SW Salutes; 13.5 ± 0.2 mg Se/kg, n = 5) was added to the basal diet at 0.74, 1.48, and 2.22 g/kg and that of oats (Loyal; 2.5 ± 0.1 mg Se/kg, n = 5) at 4.07, 8.15, and 12.22 g/kg to provide 20, 30, or 40 μg Se/kg diet, respectively. Each diet was analyzed for Se before it was provided to animals (Table 2).

Experimental Design. One hundred and eight male weanling Sprague−Dawley rats (strain SAS:VAF; Charles River, Wilmington, MA) were used in the present study; 96 of them were fed the basal diet to deplete them of Se, and 12 were fed the Se-adequate diet as positive controls. The Se depletion was determined by measuring GPX activity in whole blood collected via tail artery, comparing the results from rats fed the basal diet and the Se-adequate diet. The Se depletion was confirmed after 56 days on the basal diet, when the difference in blood GPX activity between the groups was significant (34.9 ± 2.8 vs 577.1 ± 27.5 U/mg Hb, $P < 0.05$; n = 5). The Se-depleted rats were then randomly assigned into 13 dietary groups consisting of the basal diet (n = 12) or that diet supplemented with 10, 20, 50, 70, 100, or 150 μg Se/kg from SeMet (n = 8) or 20, 30, or 40 μg Se/kg from yellow peas or oats (n = 6). The Se repletion period was 50 days.

Table 2. Selenium Content of the Experimental Diets[a]

	targeted Se concn (μg/kg)	analyzed Se concn (μg/kg)
30% Torula yeast basal diet	5	4.1 ± 1.8
Se supplement		
selenomethionine	10	10.9 ± 1.3
	20	20.5 ± 1.3
	50	57.7 ± 2.0
	70	79.1 ± 1.2
	100	96.1 ± 0.4
	150	140.8 ± 13.2
peas	20	13.2 ± 2.1
	30	23.9 ± 2.4
	40	29.0 ± 1.6
oats	20	15.0 ± 0.7
	30	23.8 ± 0.7
	40	33.5 ± 0.9

[a] Values are the mean ± SD, n = 21 for the 30% Torula yeast basal diet, n = 6 for the Se-adequate diet (150 μg Se/kg), and n = 3 for each of the other diets. concn = concentration.

Rats were individually housed in stainless steel cages with wire-mesh bottoms in a room maintained at 50% relative humidity, 22 °C, and a 12 h light/dark cycle. All rats had free access to diet and deionized water, and they were weighed weekly. Food intake was recorded on days 74−78 during the Se repletion period (n = 4 per group). At the end of the experiment, rats were anesthetized with a mixture of ketamine and xylazine. Blood, liver, gastrocnemius muscle, and kidneys were collected immediately and stored at −80 °C for enzyme and Se analyses. Liver, muscle, and kidneys were lyophilized prior to Se analysis.

Enzyme Assays. Glutathione peroxidase activity was determined in whole blood and liver according to the method of Paglia and Valentine[29] as modified by Lawrence and Burk[30] using H_2O_2 as the substrate in the presence of azide. The activity in whole blood was expressed as units per milligram of hemoglobin (Hb) and in liver as units per milligram of protein; 1 unit of activity was defined as the amount of enzyme required to oxidize 1.0 μmol of NADPH per minute. Thioredoxin reductase activity was determined in liver according to the method of Hill et al.[31] as modified by Hintze et al.[32] A unit of activity was defined as 1.0 μmol of thionitrobenzoate formed per minute per milligram of protein). Protein concentrations were quantified according to the Bradford method (Bio-Rad, Hercules, CA).

Selenium Analysis. Samples of diets, plasma, and tissues were digested by a mixture of nitric acid, hydrochloric acid, and magnesium nitrate. Digested samples were analyzed by hydride generation, inductively coupled argon plasma mass spectrometry (Perkin-Elmer DRCII instrument, Perkin-Elmer Corp., Wellesley, MA), equipped with automated hydride generation and a flow injection system. Each sample was digested in triplicate, and the average of these measurements was taken as the final result for each sample analyzed. Results of the analysis were expressed as micrograms per kilogram for diets (dry weight), micromoles per liter for plasma, and micromoles per kilogram for liver, muscle, and kidneys (dry weight).

Statistical Analyses. Student's t test was used to compare differences between groups fed the basal and the Se-adequate diets. One-way

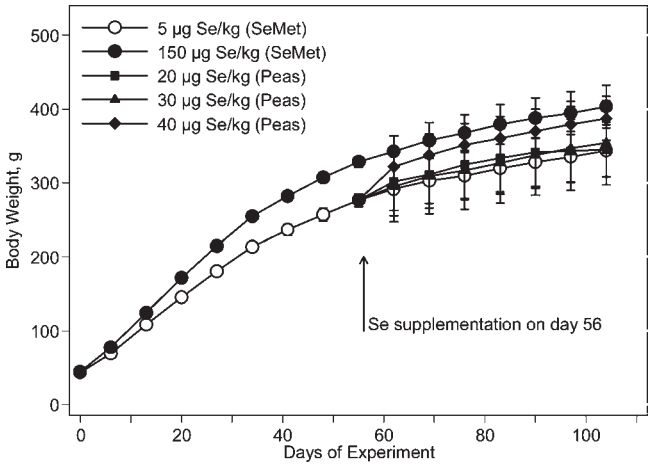

Figure 1. Body weight of rats during the Se depletion and the Se repletion periods. Student's *t* test was used to compare the difference between groups fed the basal and the Se-adequate diets throughout the experiment. One-way analysis of variance followed by Tukey contrasts was used to compare differences among groups during the Se repletion period. Dietary supplementation with yellow peas or oats (data not shown) during the Se repletion period tended to increase body weight, but neither increase was significant. Data shown are the mean ± SD, n = 12 for groups fed the basal and the Se-adequate diets and n = 6 for groups fed the pea- or oat-supplemented diets.

analysis of variance followed by Tukey contrasts was used to test differences between the Se-deficient group and the groups fed pea- or oat-supplemented diets with different amounts of Se. A slope-ratio model[33] was used to determine the relative bioavailability of Se from peas and oats compared to Se from SeMet. The linearity of the respective regression lines was ascertained for each source of Se, after which a single multiple-regression model was derived to determine the slope and intercept of the responses for the three Se sources: SeMet, yellow peas, and oats.[34] Confidence limits for relative bioavailability were obtained according to Fieller's method.[33] All data are presented as the mean ± SD. Differences with $P \leq 0.05$ are considered to be significant. All statistical analyses were performed using SAS version 9.2 (SAS Institute, Inc., Cary, NC).

RESULTS

The targeted and the actual analyzed Se concentrations of the basal and experimental diets are in Table 2. The average analyzed Se concentration of the basal diet was 4.1 μg/kg compared with the recommended Se concentration of the AIN-93G formulation (150 μg/kg).[26] The targeted levels of Se supplementation were 20, 30, and 40 μg Se/kg, and the actual analyzed concentrations of Se were 13, 24, and 29 μg/kg with the pea-supplemented diets and 15, 24, and 34 μg/kg with the oat-supplemented diets, respectively (Table 2). This difference between the targeted and analyzed Se concentrations was caused by a variation in Se from the available lots of Torula yeast, which varied from 2.4 ± 0.3 to 48.3 ± 0.6 μg Se/kg. Because the analyzed Se concentrations of these diets met the requirements of the slope-ratio model,[33] (a) graded levels of dietary Se and (b) intakes of Se must not exceed the amount required to fully replenish the response measure, these diets were used for the experiment without further adjustment for Se concentrations.

Feeding rats the Se-deficient basal diet retarded growth. After 21 days on the diet, the average body weight of rats fed the basal diet was 145.8 ± 13.1 g compared with those fed the Se-adequate diet

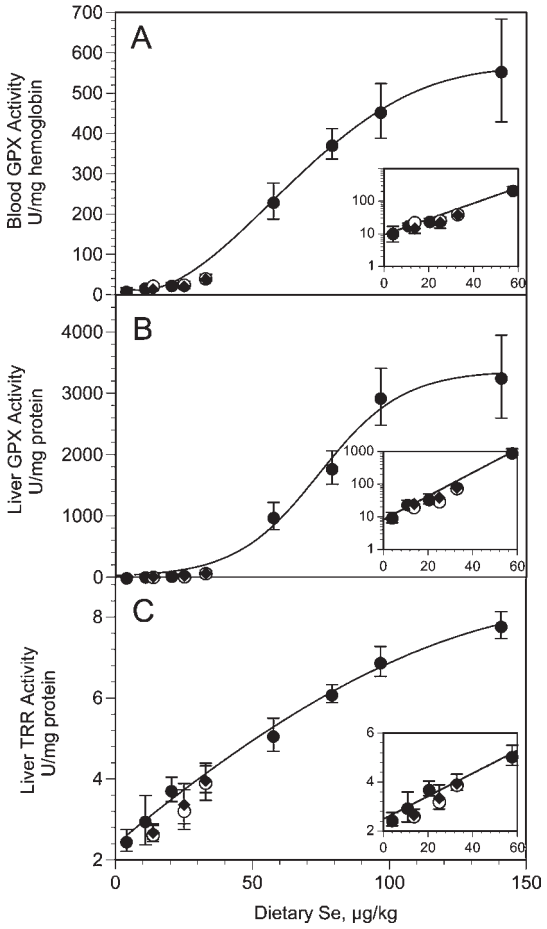

Figure 2. Responses of blood GPX (A), liver GPX (B), and liver TRR activities (C) to dietary supplementation with SeMet (●), yellow peas (○), and oats (◆). For the slope-ratio analyses, blood and liver GPX activities were log-transformed to achieve linearity. Data shown are the mean ± SD, n = 8 for SeMet supplementation and n = 6 for pea or oat supplementation.

(171.8 ± 9.2 g; $P < 0.01$), and this difference between the groups remained statistically significant throughout the experiment (Figure 1). Dietary supplementation with Se from peas (Figure 1) or oats (data not shown) tended to increase body weight; however, neither increase was statistically significant. The 5-day average food intakes of rats fed the basal diet and rats fed the Se-adequate diet during the Se repletion period were 16.8 ± 0.8 and 17.8 ± 0.6 g/day (P = 0.05), respectively. Dietary supplementation with peas or oats at 20 and 30 μg Se/kg did not significantly increase food intake compared with the basal diet whereas that at 40 μg Se/kg did (18.7 ± 1.8 g/day for peas and 18.6 ± 1.7 g/day for oats, $P \leq 0.05$), whereas that at 40 μg Se/kg did.

Feeding rats the basal diet decreased blood GPX activity. At the end of the experiment, the blood GPX activity of the rats fed the basal diet was only 1% of that of rats maintained on the Se-adequate diet throughout the experiment (7.1 ± 2.8 vs 726.9 ± 103.2 U/mg Hb; n = 8). Dietary supplementation with SeMet resulted in a dose-dependent increase in blood GPX activity (Figure 2A). At the end of the Se repletion period, the GPX activity was 470.2 ± 35.5 U/mg Hb in the group replenished with 150 μg Se/kg from SeMet, which represented a 64.7% restoration of GPX activity compared with the rats fed the Se-adequate diet throughout the experiment. Adding peas or oats to

Table 3. Relative Biological Value (RBV; Bioavailability) of Selenium from Yellow Peas and Oats to Selenomethionine in Rats[a]

	% RBV (95% confidence interval)	
	peas	oats
blood GPX	86.3 (71.5, 101.1)	80.7 (67.8, 93.5)
liver GPX	84.2 (72.6, 95.8)	84.6 (76.7, 92.4)
liver TRR	83.0 (56.0, 109.9)	83.5 (65.4, 101.5)
plasma Se	95.4 (85.4, 105.4)	94.4 (86.7, 102.2)
liver Se	103.5 (91.9, 115.0)	108.4 (98.5, 118.2)
muscle Se	70.7 (57.3, 84.2)	104.6 (92.3, 116.8)
kidney Se	93.9 (86.1, 101.6)	89.5 (83.4, 95.6)
mean ± SD[b]	88.1 ± 10.6	92.2 ± 10.8

[a] Standard response curve for Se-dependent enzyme activities and tissue Se concentrations was made by feeding rats diets containing various amounts of Se as SeMet. The enzyme activities and tissue Se concentrations of rats fed the pea- or oat-supplemented diets were compared with the values on the standard response curve. The % RBV was estimated by using the slope-ratio method[33] for enzyme activities or the parallel line assay for tissue Se.[33]. [b] The overall mean of each % RBV column.

the basal diet resulted in a log−linear, dose-dependent increase in GPX activity (Figure 2A). The slope-ratio model[33] showed that Se bioavailability was 86.3% for peas and 80.7% for oats, relative to SeMet (Table 3).

The decrease in liver GPX activity by Se depletion was similar to that of blood GPX activity. At the end of the experiment, the hepatic GPX activity of the rats fed the basal diet was no greater than 1% of those maintained on the Se-adequate diet (10.2 ± 3.6 vs 3972.5 ± 929.8 U/mg protein; n = 8). The enzyme activity responded to dietary SeMet supplementation (Figure 2B). At the end of the Se repletion period, the liver GPX activity was 3271.4 ± 675.7 U/mg protein in the group supplemented with 150 μg Se/kg as SeMet, which represented an 82.4% restoration of GPX activity compared with the group fed the Se-adequate diet throughout the experiment. Dietary supplementation with Se from peas or oats resulted in a log−linear, dose-dependent increase in liver GPX activity (Figure 2B), indicating that Se bioavailability was 84.2% for peas and 84.6% for oats, compared to SeMet (Table 3).

Hepatic TRR activity responded to changes in dietary Se (Figure 2C). At the end of the experiment, the TRR activity of the rats fed the basal diet was 34% of that of the rats maintained on the Se-adequate diet throughout the experiment (2.5 ± 0.3 vs 8.0 ± 0.6 U/mg protein; n = 8). At the end of the Se repletion period, the enzyme activity was 7.8 ± 0.3 U/mg protein in the group supplemented with 150 μg Se/kg as SeMet, which represented a 97.5% restoration of TRR activity. Adding peas or oats to the basal diet resulted in a linear, dose-dependent increase in hepatic TRR activity (Figure 2C), showing Se bioavailabilities of 83.0 and 83.5% for peas and oats, respectively, relative to SeMet (Table 3).

Feeding rats the Se-deficient basal diet depleted tissue Se. At the end of the experiment, Se concentrations of plasma, liver, gastrocnemius muscle, and kidneys of the rats fed the basal diet were 2, 1, 1, and 6%, respectively, compared to those fed the Se-adequate diet (0.1 ± 0.1 vs 6.5 ± 0.6 μmol/L for plasma, 0.5 ± 0.2 vs 40.0 ± 4.8 μmol/kg for liver, 0.1 ± 0.1 vs 7.5 ± 0.6 μmol/kg for muscle, and 4.2 ± 0.7 vs 72.2 ± 5.7 μmol/kg for kidneys). Dietary supplementation with SeMet resulted in a dose-dependent increase in tissue Se (Figure 3). At the end of the repletion period, the maximum restoration of Se was 93.8, 89.0, 77.3, and 90.0%, respectively, in plasma, liver, muscle, and kidneys of the rats replenished with the 150 μg Se/kg diet (6.1 ± 0.9 μmol/L in plasma, 35.6 ± 3.7, 5.8 ± 0.9, and 65.0 ± 7.0 μmol/kg in liver, muscle, and kidneys, respectively) compared to the rats fed the Se-adequate diet throughout the experiment. Adding peas or oats to the basal diet during the Se-repletion period resulted in linear or log−linear, dose-dependent increases in Se in those tissues (Figure 3). The relative bioavailabilities of Se from peas were 95.4% (plasma), 103.5% (liver), 70.7% (muscle), and 93.9% (kidneys), and those of Se from oats were 94.4% (plasma), 108.4% (liver), 104.6% (muscle), and 89.5% (kidneys), respectively, compared with SeMet (Table 3).

DISCUSSION

In the present study, we assessed bioavailabilities of Se from naturally produced high-Se yellow peas and oats on the basis of restoration of Se-dependent enzyme activities and tissue Se retention in Se-depleted rats. A low-Se status was induced in rats by feeding them a Torula yeast-based Se deficient diet for 56 days and then replenishing Se by supplementing the diet with high-Se peas or oats. Previous findings from our laboratory[19−21] and others[35] demonstrated the validity of this method in assessing the bioavailability of Se from foods. We demonstrated that dietary supplementation with Se from yellow peas or oats in a range from 20 to 40 μg Se/kg generated linear or log−linear, nonplateauing responses in Se-dependent enzyme activities and tissue Se contents, which were used to extrapolate bioavailabilities relative to that of SeMet.

The bioavailability of Se is defined as the fraction of ingested dietary Se that is utilized for normal physiological functions. The main biological function of GPX is to protect organisms from oxidative damage,[36] and TRR plays important roles in antioxidant defense and in cell cycling control.[37] Glutathione peroxidase and TRR activities were used to assess the amount of Se from peas and oats incorporated into the SeCys compartment for specific seleno-protein synthesis. Dietary supplementation with either peas or oats produced dose-dependent increases in GPX and TRR activities that were similar to those of SeMet, which indicates that Se from these two foods is as efficient in digestibility, absorbability, and metabolic conversion to functional SeCys-enzymes as that in SeMet. Whereas both seleno-enzyme activities and tissue Se responded to the amount of bioavailable Se consumed, restoration of SeCys-enzyme activities in Se-depleted animals has particular physiological relevance because of their biological functions.

The retention of Se in tissues is an indirect measure of Se bioavailability. The Se in blood, liver, muscles, and kidneys constitutes 60% of total body Se in humans.[38] In the present study, Se from either peas or oats was comparable to Se from SeMet in replenishing Se concentrations in plasma, liver, gastrocnemius muscle, and kidneys. Increases in Se concentrations in these tissues are most likely the result of nonspecific incorporation of SeMet into tissue proteins. The observed increases in both tissue Se concentrations and seleno-enzyme activities in rats fed the pea- and oat-supplemented diets indicate that Se from these foods is not only catabolized to enter the SeCys

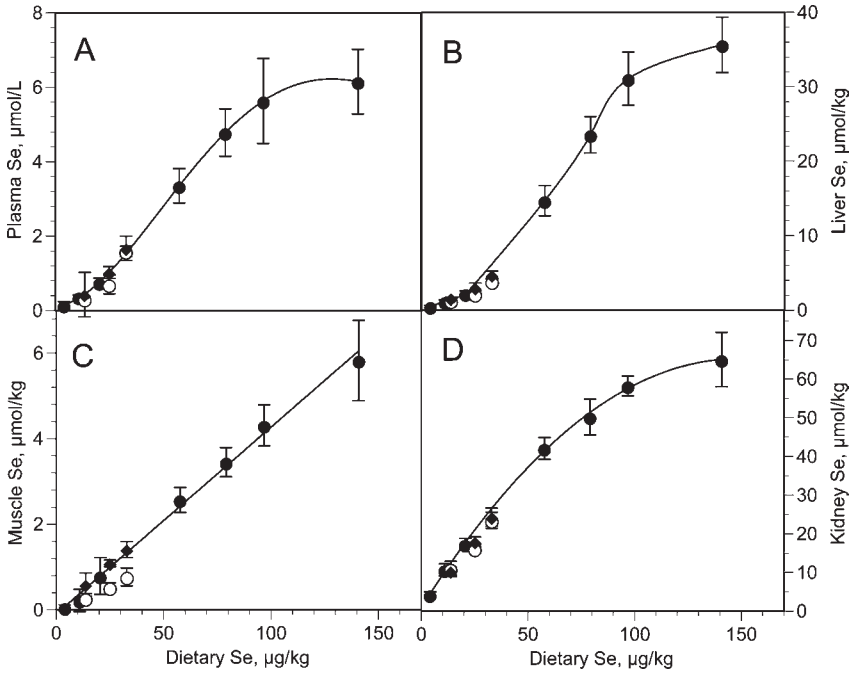

Figure 3. Responses of plasma (A), liver (B), gastrocnemius muscle (C), and kidneys (D) to dietary Se supplementation with SeMet (●), peas (○), and oats (◆). For the slope-ratio analyses, liver Se concentrations were log-transformed to achieve linearity. Data shown are the mean ± SD, $n = 8$ for SeMet supplementation and $n = 6$ for pea or oat supplementation.

compartment but also significantly retained in the nonspecific SeMet compartment.

Consumption of the Se-deficient basal diet retarded growth in rats. Torula yeast was the protein source for the diet because it was very low in Se. Except for Se, the diet contained all required nutrients, including sulfur-containing amino acids, minerals, and vitamins in quantities that met or exceeded the NRC recommendations[28] and the AIN-93G formulation.[26] The only differences between the basal diet and experimental diets were their amounts and sources of Se. We noted significant increases in food intake in groups fed 40 mg Se/kg from peas or oats and corresponding increases in body weights in these groups. This indicates that the quantity of Se in the diet was responsible for the changes in food intake and body weight observed in this study.

We used a slope-ratio model[33] to determine the relative bioavailability of Se from yellow peas and oats compared to Se from SeMet. In this model, linear or log−linear regression lines are generated for both test and standard compounds, and the relative bioavailability is expressed as the ratio of the slope of the test compound to that of the standard. Furthermore, use of this method requires (a) graded levels of the test compounds, (b) intakes of the test compound that do not exceed the amount required to fully replenish the response measure, and (c) regression lines for test and reference treatments sharing a common intercept. Using these guidelines, we designed our study to use peas and oats in amounts that provided 20, 30, and 40 μg Se/kg diet. Although the analyzed Se concentrations of the pea- and oat-supplemented diets did not achieve targeted values, they were within the designed concentration range and gave dose-dependent relationships. For all regressions, we used the standard response levels between 5 and 70 μg Se/kg, because at levels >70 μg Se/kg the responses for some enzymes and tissue Se became nonlinear or reached a plateau. The linearity of the respective regression lines was ascertained for each source of Se, after which a single multiple-regression model was derived to determine the slope and intercept of the responses for the three Se sources, peas, oats, and SeMet.[34] As a result, this approach generated linear or log−linear, dose-dependent increases in Se enzyme activities and tissue Se concentrations and accurate estimates of bioavailabilities relative to those from SeMet.

Selenium is an essential trace element. Because of its wide variation in geographic distribution, there are regions in the world (e.g., Europe and parts of China) where Se is deficient from natural resources, and intake of Se in many countries is below recommended levels.[39] Generally, organic forms of Se (e.g., SeMet, Se-yeast, and wheat Se) are more bioavailable than inorganic Se (e.g., selenite and selenate), and plant foods are the most common dietary sources of Se. Thus, naturally produced high-Se foods, including peas and oats, may provide needed Se for humans and livestock, particularly for those in Se-deficient regions.

In conclusion, the present study demonstrated that Se from yellow peas and oats was highly bioavailable. Compared with SeMet, these natural sources of Se were capable of restoring Se-dependent enzyme activities and tissue Se concentrations in Se-deficient rats. Thus, naturally produced high-Se yellow peas and oats may be a good dietary source of Se.

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■ REFERENCES

(1) Schwarz, K.; Foltz, C. M. Selenium as an integral part of factor 3 against dietary necrotic liver degeneration. *J. Am. Chem. Soc.* **1957**, *79* (12), 3292–3293.

(2) Rotruck, J. T.; Pope, A. L.; Ganther, H. E.; Swanson, A. B.; Hafeman, D. G.; Hoekstra, W. G. Selenium: biochemical role as a component of glutathione peroxidase. *Science* **1973**, *179* (73), 588–590.

(3) Gladyshev, V. N.; Jeang, K. T.; Stadtman, T. C. Selenocysteine, identified as the penultimate C-terminal residue in human T-cell thioredoxin reductase, corresponds to TGA in the human placental gene. *Proc. Natl. Acad. Sci. U.S.A.* **1996**, *93* (12), 6146–6151.

(4) Chen, X.; Yang, G.; Chen, J.; Chen, X.; Wen, Z.; Ge, K. Studies on the relations of selenium and Keshan disease. *Biol. Trace Elem. Res.* **1980**, *2* (2), 91–107.

(5) Ge, K.; Xue, A.; Bai, J.; Wang, S. Keshan disease-an endemic cardiomyopathy in China. *Virchows Arch. A: Pathol. Anat. Histopathol.* **1983**, *401* (1), 1–15.

(6) Ammerman, C. B.; Miller, S. M. Selenium in ruminant nutrition: a review. *J. Dairy Sci.* **1975**, *58* (10), 1561–1577.

(7) Broome, C. S.; McArdle, F.; Kyle, J. A.; Andrews, F.; Lowe, N. M.; Hart, C. A.; Arthur, J. R.; Jackson, M. J. An increase in selenium intake improves immune function and poliovirus handling in adults with marginal selenium status. *Am. J. Clin. Nutr.* **2004**, *80* (1), 154–162.

(8) Negro, R.; Greco, G.; Mangieri, T.; Pezzarossa, A.; Dazzi, D.; Hassan, H. The influence of selenium supplementation on postpartum thyroid status in pregnant women with thyroid peroxidase autoantibodies. *J. Clin. Endocrinol. Metab.* **2007**, *92* (4), 1263–1268.

(9) Clark, L. C.; Combs, G. F. J.; Turnbull, B. W.; Slate, E. H.; Chalker, D. K.; Chow, J.; Davis, L. S.; Glover, R. A.; Graham, G. F.; Gross, E. G.; Krongrad, A.; Lesher, J. L. J.; Park, H. K.; Sanders, B. B. J.; Smith, C. L.; Taylor, J. R. Effects of selenium supplementation for cancer prevention in patients with carcinoma of the skin. A randomized controlled trial. Nutritional Prevention of Cancer Study Group. *JAMA, J. Am. Med. Assoc.* **1996**, *276* (24), 1957–1963.

(10) Low, S. C.; Harney, J. W.; Berry, M. J. Cloning and functional characterization of human selenophosphate synthetase, an essential component of selenoprotein synthesis. *J. Biol. Chem.* **1995**, *270* (37), 21659–21664.

(11) Sunde, R. A.; Evenson, J. K. Serine incorporation into the selenocysteine moiety of glutathione peroxidase. *J. Biol. Chem.* **1987**, *262* (2), 933–937.

(12) Tormay, P.; Wilting, R.; Lottspeich, F.; Mehta, P. K.; Christen, P.; Bock, A. Bacterial selenocysteine synthase − structural and functional properties. *Eur. J. Biochem.* **1998**, *254* (3), 655–661.

(13) Olson, O. E.; Novacek, E. J.; Whitehead, E. I.; Palmer, I. S. Investigations on selenium in wheat. *Phytochemistry* **1970**, *9*, 1181–1188.

(14) Yasumoto, K.; Suzuki, T.; Yoshida, M. Identification of selenomethionine in soybean protein. *J. Agric. Food Chem.* **1988**, *36*, 463–467.

(15) Sathe, S. K.; Mason, A. C.; Weaver, C. M. Some properties of a selenium-incorporating sulfur-rich protein in soybeans (*Glycine max* L.). *J. Agric. Food Chem.* **1992**, *40* (11), 2077–2083.

(16) Kubota, J.; Allaway, W. H. In *Geographic Distribution of Trace Element Problems, Micronutrients in Agriculture, Muscle Soals, Alabama, 1971*; Soil Science Society of America: Muscle Soals, AL, 1971; pp 525−554.

(17) Kubota, J.; Allaway, W. H.; Carter, D. L.; Cary, E. E.; Lazar, V. A. Selenium in crops in the United States in relation to selenium-responsive diseases of animals. *J. Agric. Food Chem.* **1967**, *15* (3), 448–453.

(18) Wolnik, K. A.; Fricke, F. L.; Capar, S. G.; Braude, G. L.; Meyer, M. W.; Satzger, R. D.; Kuennen, R. W. Elements in major raw agricultural crops in the United States. 2. Other elements in lettuce, peanuts, potatoes, soybeans, sweet corn, and wheat. *J. Agric. Food Chem.* **1983**, *31* (6), 1244–1249.

(19) Reeves, P. G.; Gregoire, B. R.; Garvin, D. F.; Hareland, G. A.; Lindlauf, J. E.; Johnson, L. K.; Finley, J. W. Determination of selenium bioavailability from wheat mill fractions in rats by using the slope-ratio assay and a modified Torula yeast-based diet. *J. Agric. Food Chem.* **2007**, *55* (2), 516–522.

(20) Yan, L.; Reeves, P.; Johnson, L. Assessment of selenium bioavailability from naturally produced high-selenium soy foods in selenium-deficient rats. *J. Trace Element Med. Biol.* **2010**, *24* (4), 223–229.

(21) Reeves, P. G.; Leary, P. D.; Gregoire, B. R.; Finley, J. W.; Lindlauf, J. E.; Johnson, L. K. Selenium bioavailability from buckwheat bran in rats fed a modified AIN-93G torula yeast-based diet. *J. Nutr.* **2005**, *135* (11), 2627–2633.

(22) USDA National Nutrient Database for Standard Reference, release 23, 2010.

(23) Anderson, V.; Lardy, G. P.; Ilse, B. Field pea grain for beef cattle. *Prof. Anim. Sci.* **2007**, *23*, 1–7.

(24) Johnson, L.; Boyles, S. Oats as a feed for beef cattle; NDSU Extension Service AS-1020, 1991; available at http://www.ag.ndsu.edu/pubs/ansci/beef/as1020w.htm.

(25) National Research Council. *Guide for the Care and Use of Laboratory Animals*; National Academy Press: Washington, DC, 1996.

(26) Reeves, P. G.; Nielsen, F. H.; Fahey, G. C. J. AIN-93 purified diets for laboratory rodents: final report of the American Institute of Nutrition ad hoc writing committee on the reformulation of the AIN-76A rodent diet. *J. Nutr.* **1993**, *123* (11), 1939–1951.

(27) Jurgens, M. H. Feed stuffs used in livestock diets. In *Animal Feeding and Nutrition*, 8th ed.; Kendall/Hunt: Dubuque, IA, 1997; pp 81−234.

(28) National Research Council. *Nutrient Requirements of Laboratory Animals*, 4th rev. ed.; National Academy Press: Washington, DC, 1995; pp 3−79.

(29) Paglia, D. E.; Valentine, W. N. Studies on the quantitative and qualitative characterization of erythrocyte glutathione peroxidase. *J. Lab. Clin. Med.* **1967**, *70* (1), 158–169.

(30) Lawrence, R. A.; Burk, R. F. Glutathione peroxidase activity in selenium-deficient rat liver. *Biochem. Biophys. Res. Commun.* **1976**, *71* (4), 952–958.

(31) Hill, K. E.; McCollum, G. W.; Burk, R. F. Determination of thioredoxin reductase activity in rat liver supernatant. *Anal. Biochem.* **1997**, *253* (1), 123–125.

(32) Hintze, K. J.; Wald, K. A.; Zeng, H.; Jeffery, E. H.; Finley, J. W. Thioredoxin reductase in human hepatoma cells is transcriptionally regulated by sulforaphane and other electrophiles via an antioxidant response element. *J. Nutr.* **2003**, *133* (9), 2721–2727.

(33) Finney, D. J. *Statistical Method in Biological Assay*, 3rd ed.; Charles Griffin: London, U.K., 1978.

(34) Littell, R. C.; Henry, P. R.; Lewis, A. J.; Ammerman, C. B. Estimation of relative bioavailability of nutrients using SAS procedures. *J. Anim. Sci.* **1997**, *75* (10), 2672–2683.

(35) Ornsrud, R.; Lorentzen, M. Bioavailability of selenium from raw or cured selenomethionine-enriched fillets of Atlantic salmon (*Salmo salar*) assessed in selenium-deficient rats. *Br. J. Nutr.* **2002**, *87* (1), 13–20.

(36) Mills, G. C. Hemoglobin catabolism. I. Glutathione peroxidase, an erythrocyte enzyme which protects hemoglobin from oxidative breakdown. *J. Biol. Chem.* **1957**, *229* (1), 189–197.

(37) Sun, Q. A.; Wu, Y.; Zappacosta, F.; Jeang, K. T.; Lee, B. J.; Hatfield, D. L.; Gladyshev, V. N. Redox regulation of cell signaling by selenocysteine in mammalian thioredoxin reductases. *J. Biol. Chem.* **1999**, *274* (35), 24522–24530.

(38) Sunde, R. A. Selenium. In *Biochemical, Physiological, Molecular Aspects of Human Nutrition*, 2nd ed.; W. B. Saunders: New York, 2006; pp 1091−1126.

(39) Rayman, M. P. The use of high-selenium yeast to raise selenium status: how does it measure up? *Br. J. Nutr.* **2004**, *92* (4), 557–573.