A Systematic Screening of Total Antioxidants in Dietary Plants[1]

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ABSTRACT A predominantly plant-based diet reduces the risk for development of several chronic diseases. It is often assumed that antioxidants contribute to this protection, but results from intervention trials with single antioxidants administered as supplements quite consistently do not support any benefit. Because dietary plants contain several hundred different antioxidants, it would be useful to know the total concentration of electron-donating antioxidants (i.e., reductants) in individual items. Such data might be useful in the identification of the most beneficial dietary plants. We have assessed systematically total antioxidants in a variety of dietary plants used worldwide, including various fruits, berries, vegetables, cereals, nuts and pulses. When possible, we analyzed three or more samples of dietary plants from three different geographic regions in the world. Total antioxidants was assessed by the reduction of Fe^{3+} to Fe^{2+} (i.e., the FRAP assay), which occurred rapidly with all reductants with half-reaction reduction potentials above that of Fe^{3+}/Fe^{2+}. The values, therefore, expressed the corresponding concentration of electron-donating antioxidants. Our results demonstrated that there is more than a 1000-fold difference among total antioxidants in various dietary plants. Plants that contain most antioxidants included members of several families, such as Rosaceae (dog rose, sour cherry, blackberry, strawberry, raspberry), Empetraceae (crowberry), Ericaceae (blueberry), Grossulariaceae (black currant), Juglandaceae (walnut), Asteraceae (sunflower seed), Punicaceae (pomegranate) and Zingiberaceae (ginger). In a Norwegian diet, fruits, berries and cereals contributed 43.6%, 27.1% and 11.7%, respectively, of the total intake of plant antioxidants. Vegetables contributed only 8.9%. The systematic analysis presented here will facilitate research into the nutritional role of the combined effect of antioxidants in dietary plants. J. Nutr. 132: 461–471, 2002.

KEY WORDS: • *antioxidants* • *berries* • *fruits* • *vegetables* • *diet* • *humans*

A general consensus has been reached during the last few years that diet has a major role in the development of chronic diseases, such as cancer, coronary heart disease, obesity, diabetes type 2, hypertension and cataract (1–9). This consensus suggests that a predominantly plant-based diet rich in fruits and vegetables, pulses and minimally processed starchy staple foods reduces the risk for development of these diseases significantly. The recommendations, which are mainly based on epidemiological studies are thus, that fruits, vegetables and less processed staple foods provide the best protection against the development of disease with little or no merit in recommending vitamin or other micronutrient supplements for disease prevention (1–9). This is a safe principle that promises to provide for improved public health. However, these general recommendations avoid the issue of which dietary plants to eat. A large and remaining challenge, therefore, is to identify the most beneficial dietary plants. Furthermore, a complete understanding of etiologic pathways leading to chronic disease would include identification of the protective substances in the plants and the mechanisms by which they protect against disease development.

A common denominator in pathogenesis of most chronic diseases is the involvement of oxidative stress, related to the production by all aerobic organisms of reactive oxygen and nitrogen species, including free radicals (10–15). In addition to having a role in intra- and extracellular signaling, these reactive molecular species may initiate damaging biochemical reactions (14–16). In response to such damage, a complex antioxidant defense has developed, and dietary antioxidants comprise an important role in this defense (17–20).

Although it has often been assumed that antioxidants in dietary plants protect against oxidative stress-related diseases, results from intervention trials with single compounds such as vitamins E and C or β-carotene have not supported any protective effect (13,17–22). Indeed, supplementation with β-carotene has resulted in adverse disease outcomes in clinical trials (23–26). One reason for the ineffective clinical trials could be that the protective effects of fruits and vegetables result from the action of lesser-known antioxidant compounds

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or from a concerted action of the cocktail of antioxidants present in foods. This would be in accordance with the observation that brussels sprouts, onion and tomatoes (27–30) but not single antioxidants such as β-carotene, vitamins E, vitamin C or coenzyme Q_{10} are able to reduce the excretion of biomarkers for free radical DNA damage in urine or lymphocytes in humans (18,21,22,31,32).

A concerted action of a number of dietary antioxidants might also be expected from the exceedingly complex physical structure that makes up an individual. The human body, its tissues and organ, cells and macromolecules, consist of compartments with a range of physical variables, anatomical subdivisions and water- and lipid-soluble phases. Within these phases and at interfaces between phases, there will be numerous chemical variables such as pH, ionic strength, osmolality, electrical charge and chemical concentration. These variables will influence the ability of the phases to act as solvents for lipid- and water-soluble antioxidants. Because some water-soluble antioxidants have low partition coefficients into a lipid-soluble phase, their entry or retention in a water-soluble phase will be dependent upon their pKa and the pH gradient across the membrane. In addition, antioxidants with both hydrophobic and hydrophilic characteristics may be distributed between water- and lipid-soluble phases dependent upon the relative contribution and stereochemistry of hydrophobic and hydrophilic substitutions. Solubility is further modified when an antioxidant is conjugated or bound into more complex substances such as proteins.

One theoretical but likely possibility is, therefore, that antioxidants with different partition coefficients will recharge neighboring antioxidants in an integrated and complementary manner. Such interaction has been proven in vitro for α-tocopherol, α-tocotrienol, vitamin C, lipoic acid and thiols by Packer and colleagues (20), but the concept could have much broader validity as suggested by Buettner (33). This raises the prospect that a variety of antioxidants are necessary to maintain the proper redox status in a nonhomogeneous biological system. This would be similar to the coordinated reduction-oxidation reactions that occur during the respiratory chain in mitochondria.

The amount of well-known antioxidants, such as α-tocopherol, vitamin C and β-carotene in dietary plants has been measured in detail. However, recent data may suggest that a relatively small part of the antioxidants in most dietary plants is contributed by the well-known antioxidants (34,35). Although it would be much simpler to test the protective effect of single or a limited number of antioxidants, we may never find such an association if it actually is the case that a number, maybe hundreds, of dietary antioxidants, such as carotenoids, polyphenolic acids, sulfides, flavonoids, lignans, etc., are bioactive and work synergistically. Thus, the total amount of electron-donating antioxidants (i.e., reductants) in the diet, derived from combinations of individual antioxidants that occur naturally in foods, may be a better concept than individual dietary antioxidants.

In previous studies, three methods have been used to assess the total antioxidant capacity of a few dietary plants. The 6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid (Trolox) equivalent antioxidant capacity (TEAC)[3] assay of Miller et al. (36), the ferric-reducing ability of plasma (FRAP) assay of Benzie and Strain (37), and the oxygen radical absorbance capacity (ORAC) assay of DeLange and Glazer (38) and others (39). The TEAC and the ORAC assay are based on the antioxidant's ability to react with or neutralize free radicals generated in the assay systems, whereas the FRAP assay measures the reduction of Fe^{3+} (ferric iron) to Fe^{2+} (ferrous iron) in the presence of antioxidants. Because the ferric-to-ferrous iron reduction occurs rapidly with all reductants with half-reaction reduction potentials above that of Fe^{3+}/Fe^{2+}, the values in the FRAP assay will express the corresponding concentration of electron-donating antioxidants.

We elected to use the FRAP analysis for several reasons. The FRAP assay is the only assay that directly measures antioxidants or reductants in a sample. The other assays are more indirect because they measure the inhibition of reactive species (free radicals) generated in the reaction mixture, and these results also depend strongly on the type of reactive species used. The FRAP assay, in contrast, uses antioxidants as reductants in a redox-linked colorimetric reaction. Furthermore, the other assays, but not the FRAP assay, use a lag phase type of measurement. This has been difficult to standardize in previous experiments and has generated varying results among different laboratories. In the FRAP assay, pretreatment is not required, stoichiometric factors are constant and linearity is maintained over a wide range. One possible disadvantage with the FRAP assay is the fact that this assay does not react with thiols, because the reduction potential for thiols generally are below that of the Fe^{3+}/Fe^{2+} half-reaction. However, because only limited amounts of plant glutathione are absorbed by humans (40), and almost no other antioxidant thiols are present in dietary plants (one exception is garlic, see below), the FRAP method may be suitable for assessment of total antioxidants in plants.

In this study, we assessed systematically the concentration of total antioxidants by the FRAP assay, expressed as the combined concentrations of all electron-donating reductants, in a variety of dietary plants. These data, together with further studies on bioavailability as well as effect of processing, will greatly expand the potential for assessment of dietary intake of total antioxidants, and their relationships to pathologic processes.

METHODS

Reagents. 2,4,6-tri-pyridyl-s-triazine (TPTZ) were obtained from Fluka Chemie AG (Deisenhofen, Switzerland), sodiumacetate trihydrate and $FeSO_4 \times 7\ H_2O$ from Riedel-deHaën AG (Seelze, Germany), acetic acid and hydrochloric acid from Merck (Darmstadt, Germany), $FeCl_3 \times 6H_2O$ from BDH Laboratory Supplies (Dorset, England). MilliQ water (Millipore, Bedford, MA) and methanol of HPLC-grade obtained from Merck was used for all extractions. 2-propanol (HPLC-grade) was obtained from Merck.

Automated FRAP assay. The FRAP assay was used to measure the concentration of total antioxidants. FRAP was determined in extracts by the method of Benzie and Strain (37), with the exception that the sample was not diluted with water in the assay. A Technicon RA 1000 system (Technicon Instruments Corporation, New York, NY) was used for the measurements of absorption changes that appear when the TPTZ-Fe^{3+} complex reduces to the TPTZ-Fe^{2+} form in the presence of antioxidants. An intense blue color with absorption maximum at 593 nm develops. The measurements were performed at 600 nm. An aqueous solution of 1000 μmol/L $FeSO_4 \times 7\ H_2O$ was used for calibration of the instrument.

Sample preparation. Dietary plants were identified and classified according to standard botanic nomenclature (41–43). Samples of different commercially available dietary plants were either obtained from grocery stores or market places in several countries (see tables for details). Some items were also grown at the Agricultural University of Norway (Ås, Norway). Wild berries were picked in the loca-

[3] Abbreviations used: FRAP, ferric-reducing ability of plasma; ORAC, oxygen radical absorbance capacity; TEAC, Trolox equivalent antioxidant capacity; TPTZ, 2,4,6-tri-pyridyl-s-triazine; Trolox, 6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid.

tion indicated in the tables. All the dietary plants were analyzed directly, stored at 4°C for a few days or frozen at −20°C before analysis.

Dry samples like cereal grains were pulverized, 0.1–0.2 g was weighed out, and 1 mL of water was added. Solid samples of fruit and vegetables were chopped up in a food processor together with a certain amount of water to obtain a proper viscosity for pipetting. Methanol (9 mL) was added to 1 mL of this homogenate, and the samples were mixed and sonicated on a water bath at 0°C for 15 min. Three samples of 1.5 mL were centrifuged at 12,402 × *g* for 2 min at 4°C. The concentration of total antioxidants was measured in triplicates of the supernatant.

Validation of the FRAP analysis. The linearity of the method was investigated with standard solutions of $FeSO_4 \times 7H_2O$ and vitamin C diluted in water and in methanol, Trolox diluted in methanol, and α-tocopherol diluted in methanol and in 2-propanol. The concentrations used were between 10 and 3000 μmol/L. All concentrations were used for determination of linearity for $FeSO_4 \times 7H_2O$ in water and methanol, the six lowest concentrations were used for α-tocopherol in methanol and 2-propanol, and the five lowest concentrations were used for vitamin C in water and in methanol and for Trolox in methanol. The concentrations were chosen to give an absorbance value of 1.7 corresponding to a FRAP value of 3000 μmol/L, which was the linear range according to the instrument manual. The correlation coefficients ranged from 1.00 to 0.998.

The within-day repeatability measured as relative standard deviations (RSD%) ranged from 0.4% to 6%. The concentrations examined were 500 μmol/L ($n = 6$) and 1500 μmol/L ($n = 6$) for all solutions, and in addition, 3000 μmol/L ($n = 6$) for the $FeSO_4$ solutions. The between-day repeatability was tested for $FeSO_4$ in water and for α-tocopherol in methanol and in 2-propanol. The same iron solution was measured for 8 d, and the same α-tocopherol solutions were measured for 7 d. The RSD percentages were <3 for all samples at all concentrations tested.

Different antioxidants in different solvents (vitamin C in water, methanol and methanol:2-propanol (1 + 1); quercetin in methanol and 2-propanol; α-tocopherol in methanol, ethanol and 2-propanol; and myricetin in methanol), but at equal molar concentrations gave the same FRAP value. Thus, these solvents did not influence the examined antioxidants. It was also tested if different antioxidants in a mixture were additive. The results from the sum of single analyses of each antioxidant corresponded very well with the FRAP values found in a mixture of the same antioxidants (both in the same and in a mixture of solvents).

Statistics. Samples A, B and C in the tables represent separate samples of the same dietary plant obtained from different sources such as geographical location or manufacturer. The number of items analyzed is also indicated in the tables. The variation in the FRAP values for replicate items obtained from the same source were typically between 3 and 10 RSD percentages. Occasionally, some items had larger variation. In such cases, the FRAP values were confirmed by reanalysis.

The Pearson product-moment correlation coefficients were calculated by the Microsoft Excel software (Microsoft Corporation, Redmond, WA) for the relationship between total antioxidants in dietary plants as determined in this study and the published values, which have used other methods for assessing total antioxidant activities. To calculate the sources of plant antioxidants in the Norwegian diet we used data from the Household Budget Survey performed by the National Statistics Office. The recording period for food purchases was 2 wk, evenly distributed throughout the year (44).

RESULTS

We systematically assessed total antioxidants in a variety of dietary plants used worldwide, including various fruits, berries, vegetables, cereals, nuts and pulses. When possible, we analyzed triplicate samples or more of dietary plants from three different geographic regions of the world. If not stated otherwise in the table legend, we analyzed the whole edible portion of the fresh items. When analyzing one particular dietary plant from one geographical location, the relative SD in one sampling was typically below 10% and was always below 15%. The antioxidant concentrations of dietary plants sampled from different geographical regions were often, however, much larger. This variation in antioxidant content was probably related to the fact that different botanic variants are used but also to different cultivation conditions, extraction rates and storage conditions.

Total antioxidant content of cereals. Wholemeal flours of barley, common millet and oats contained the most antioxidants (1.09–0.59 mmol/100 g) among the cereals (**Table 1**). White flour from corn maize contained most among the white flours, followed by barley, oats and common millet. White flour contained between 23% and 54% of the antioxidant contents of wholemeal of the various cereals. Notably, white flour of wheat and grains of rice contained only 0.13 and 0.17 mmol/100 g, respectively. For some cereals, the antioxidant concentrations varied much between samplings from different geographical regions: milled white rice from United States and Mali contained 0.14 and 0.02 mmol/100 g, respectively. White flour of rice from Thailand was also exceptionally low (0.02 mmol/100 g). There are additional plants that because of their use often are grouped with the cereals, although they are botanically different (41). These (e.g., buckwheat) are often called pseudo-cereals. Wholemeal flour of the pseudo-cereal buckwheat contained 1.99 mmol antioxidants per 100 g, which is more than any of the cereals.

Total antioxidant content of roots and tubers. Roots and tubers were variable in their content of antioxidants (**Table 2**). Ginger and red beets contained very high concentrations, 3.85 and 1.98 mmol/100 g, respectively. Blue potatoes (*Solanum andigenum*) contained 0.80 mmol/100 g, while white potatoes (*Solanum tuberosum*) contained 0.09 mmol/100 g. Sweet potatoes (*Ipomoea batatas*), which belong to another botanical family, contained 0.24 mmol antioxidants per 100 g. Interestingly, carrots had the lowest antioxidant content of all the roots and tubers analyzed (i.e., 0.04 mmol/100 g). Antioxidant content in carrots from Mali was only 0.01 mmol/100 g, which is the lowest value detected in all the dietary plants analyzed.

Total antioxidant content of vegetables. There was also a large variation in antioxidant content of vegetables (**Table 3**). Vegetables, such as kale, chili pepper, red cabbage, pepper, parsley, artichoke, brussels sprouts and spinach, contained concentrations ranging from 0.98 to 2.65 mmol/100 g. The vegetables endive, cabbage, squash, fennel, cucumber and zucchini contained, however, only between 0.02 and 0.10 mmol/100 g. Thus, antioxidant content of vegetables varied more that 100-fold. Large variation was also seen within a particular botanical family such as the Brassicaceae. Members of this family, i.e., kale, red cabbage, brussels sprouts, broccoli, savoy cabbage, radish, cauliflower and cabbage, contained 2.34, 1.88, 1.14, 0.58, 0.40, 0.40, 0.18 and 0.09 mmol/100 g, respectively.

Total antioxidant content of fruits. Analyses of fruits demonstrated that pomegranate contained very high concentrations of antioxidants, i.e., 11.33 mmol/100 g (**Table 4**). Other fruits with high antioxidant content included grape, orange, plum, pineapple, lemon, date, kiwi, clementine and grapefruit, which contained between 0.83 and 1.43 mmol antioxidants per 100 g. The fruits pear, plantain and various varieties of melon contained only between 0.04 and 0.18 mmol/100 g. Notably, most members of the citrus family (Rutaceae) contained high amounts of antioxidants: orange, lemon, clementine, grapefruit and lime contained 1.14, 1.02, 0.90, 0.83 and 0.73 mmol/100 g, respectively.

Total antioxidant content of berries. The dietary plants grouped as berries (i.e., various small fruits) contained most of

TABLE 1

Total antioxidant concentrations of cereals[1]

Cereals	Botanical name	Family	Sample A[2]	*mmol/ 100 g*	Sample B	*mmol/ 100 g*	Sample C	*mmol/ 100 g*	Overall Mean
Barley, wholemeal flour	Hordeum vulgare	Poaceae	Møllerens, Norway (n = 3)[3]	1.15	Helios, Norway (n = 3)	1.18	Regal, Norway (n = 3)	0.94	1.09
Common millet, wholemeal flour	Pennisetum glaucum	Poaceae	Mali (n = 1)	0.82					0.82
Maize, white flour	Zea mays	Poaceae	Risenta, Italy (n = 3)	0.47	Moka, Slovenia (n = 3)	0.46	Prespa Import, Asia (n = 3)	0.88	0.60
Oats, rough oatmeal	Avena sativa	Poaceae	Helios, Sweden (n = 3)	0.54	Regal, Norway (n = 3)	0.54	Møllerens, Norway (n = 3)	0.70	0.59
Barley, white flour	Hordeum vulgare	Poaceae	Regal, Norway (n = 3)	0.56	Regal, Norway (n = 3)	0.60	Regal, Norway (n = 3)	0.57	0.58
Rye, wholemeal flour	Secale cereale	Poaceae	Helios, Canada (n = 3)	0.35	Regal, Norway (n = 3)	0.50	Regal, Norway (n = 3)	0.57	0.47
Wheat, wholemeal flour	Triticum aestivum	Poaceae	Helios, Canada (n = 3)	0.32	Helios, Canada (n = 3)	0.36	Regal, Norway (n = 3)	0.31	0.33
Oats, white flour	Avena sativa	Poaceae	Regal, Norway (n = 3)	0.31	Regal, Norway (n = 3)	0.32	Regal, Norway (n = 3)	0.32	0.32
Bulgur wheat, wholemeal flour	Triticum aestivum	Poaceae	Mat&Mer, Turkey (n = 3)	0.29	Namsos Import, Libanon (n = 3)	0.35	Mat&Mer, Turkey (n = 2)	0.29	0.31
Sorghum, wholemeal flour	Sorgum bicolor	Poaceae	Jalpur, England (n = 3)	0.40	Mali (n = 1)	0.19			0.30
Common millet, white flour	Pennisetum glaucum	Poaceae	E.Zwicky, Switzerland (n = 3)	0.14	Mali (n = 1)	0.36			0.25
Rye, white flour	Secale cereale	Poaceae	Regal, Norway (n = 3)	0.20	Møllerens, Norway (n = 3)	0.27	Møllerens, Norway (n = 3)	0.23	0.23
Rice, grains	Oryza sativa	Poaceae	Milled white, Eldorado, USA (n = 3)	0.14	Milled white, Mali (n = 3)	0.02	Milled brown Basmati, India (n = 3)	0.36	0.17
Wheat, white flour	Triticum aestivum	Poaceae	Mali (n = 1)	0.18	Regal, Norway (n = 3)	0.08	Møllerens, Norway (n = 3)	0.12	0.13
Durum wheat, white flour	Triticum durum	Poaceae	Meloni Grassi, Italy (n = 3)	0.06	Helios, Canada (n = 3)	0.05	Helios, Canada (n = 3)	0.05	0.05
Rice, white flour	Oryza sativa	Poaceae	Risenta, Australia (n = 3)	0.06	Thailand (n = 3)	0.02	Nutana (n = 3)	0.05	0.04
Pseudo-cereals	Botanical name	Family	Sample A		Sample B		Sample C		
Buck wheat, wholemeal flour	Fagopyrum esculentum	Polygonaceae	Helios, USA (n = 3)	1.90	Nutana (n = 3)	2.24	Helios, USA (n = 3)	1.83	1.99
Buck wheat, white flour	Fagopyrum esculentum	Polygonaceae	Nutana (n = 3)	1.01	Helios, USA (n = 3)	1.56	Nutana (n = 3)	1.13	1.23

[1] Electron-donating antioxidants were determined by the FRAP assay. Values represent mean concentration per 100 g fresh weight of edible portion if not otherwise stated. The origin, brand and cultivar are indicated for each sample, if available.

[2] Samples A, B and C represent separate samples of the same dietary plant obtained from different sources such as geographical location or manufacturer.

[3] The number of items analyzed is indicated in parentheses.

the high antioxidant dietary plants analyzed (**Table 5**). Dog rose was exceptionally high and contained ~40 mmol antioxidants per 100 g. A number of other berries also contained very high concentrations. These included crowberry, wild blueberry, black currant, sour cherry, wild blackberry, wild strawberry, cultivated blackberry and cowberry/cranberry, which all contained between 5.03 and 9.17 mmol/100 g. The cultivated varieties of blueberry and strawberry also contained high antioxidant concentrations, i.e., 3.64 and 2.17 mmol/100 g, respectively. The rose family (Rosaceae) contained many members with very high concentrations, such as dog rose, sour cherry, blackberry, strawberry, raspberry, cloudberry and rowanberry.

Total antioxidant content of pulses. Pulses, which all are members of the Fabaceae family, also contained quite variable amounts of antioxidants. Broad beans, pinto beans, ground nut and soybeans contained relatively high concentrations of antioxidants (between 0.82 and 1.86 mmol antioxidants per 100 g), whereas pulses such as mung beans, chickpeas and garden peas contained less (between 0.12 and 0.35 mmol antioxidants per 100 g; **Table 6**).

Total antioxidant content of nuts, seeds and dried fruits. Walnuts contained >20 mmol antioxidants per 100 g, that is, they are second to dog rose in antioxidant content of all the dietary plants analyzed in this study (**Table 7**). Interestingly, sunflower seeds, too, contained very high concentrations of

TABLE 2

Total antioxidant concentrations of roots and tubers[1]

Roots and tubers	Botanical name	Family	Sample A[2]	*mmol/ 100 g*	Sample B	*mmol/ 100 g*	Sample C	*mmol/ 100 g*	Overall mean
Ginger	Zingiber officinale	Zingiberaceae	Norway (n = 3)	3.49	Mali (n = 2)	4.03			3.76
Red beet	Beta vulgaris var. rubra	Chenopodiaceae	Norway (n = 3)	1.88	Norway (n = 3)	1.71	Mali (n = 3)	2.34	1.98
Blue potato	Solanum andigenum	Solanaceae	Congo, Norway (n = 3)	1.01	Congo, Norway (n = 3)	0.71	Congo, Norway (n = 3)	0.67	0.80
Swede/rutabaga	Brassica napus ssp. rapifera	Brassicaceae	Vige, Norway (n = 3)	0.37	Norway (n = 3)	0.27	Norway (n = 3)	0.56	0.40
Turnip	Brassica oleracea ssp. rapa	Brassicaceae	Mali (n = 2)	0.29					0.29
Sweet potato/ batat	Ipomoea batatas	Convolvulaceae	Carmel, Mexico (n = 3)	0.43	Red/white, Mali (n = 3)	0.16	Yellow, Mali (n = 2)	0.12	0.24
Yam	Dioscorea cayenensis	Dioscoreaceae	Mali (n = 1)	0.22					0.22
Cassava, manioc, yuka	Manihot esculenta	Euphorbiaceae	Mali (n = 1)	0.17					0.17
Potato	Solanum tuberosum	Solanaceae	Mali (n = 2)	0.13	Beate, Norway (n = 3)	0.06	Roseval, France (n = 3)	0.09	0.09
Parsnip	Pastinaca sativa	Apiaceae	Holland (n = 3)	0.08	Holland (n = 3)	0.09	France (n = 3)	0.11	0.09
Carrot	Daucus carota ssp. sativa	Apiaceae	Nantes Duke, Norway (n = 3)	0.05	Yukon, Norway (n = 3)	0.06	Mali (n = 2)	0.01	0.04

[1] Electron-donating antioxidants were determined by the FRAP assay. Values represent mean concentration per 100 g fresh weight of edible portion if not otherwise stated. The origin, brand and cultivar are indicated for each sample, if available.

[2] Samples A, B and C represent separate samples of the same dietary plant obtained from different sources such as geographical location or manufacturer.

[3] The number of items analyzed is indicated in parentheses. Blue potatoes, sweet potatoes, white potatoes and carrots were analyzed with skin on.

antioxidants (i.e., 5.39 mmol/100 g). Hazelnuts, almonds and cashew nuts contained only low concentrations (between 0.23 and 0.49 mmol/100 g). Of the dried fruits analyzed, apricots and prunes contained most antioxidants, 3.24 and 2.60 mmol/ 100 g, respectively (**Table 8**). Interestingly, the antioxidant values of raisins were much lower than the values for grapes.

Sources of plant antioxidants in the Norwegian diet. We also used our data to calculate the sources of plant antioxidants in the Norwegian diet. Based on the Household Budget Survey performed by the National Statistics Office (44), it appears that the total intake of antioxidants from dietary plants equals ~0.21 mmol per day. Fruits, berries, cereals, vegetables, roots, dried fruits and pulses contribute 43.6, 27.1, 11.7, 8.9, 7.0, 1.5 and 0.2%, respectively, of the total intake of antioxidants per day.

DISCUSSION

The present systematic analyses of a large number of dietary plants, mostly represented by items collected from three different geographical locations in the world, demonstrated that there is more than a 1000-fold difference between total antioxidants in various dietary plants. There were also large differences within each food group. The following dietary plants all contained >5.00 mmol total antioxidants per 100 g wet weight (in ranked order): dog rose, walnuts, pomegranates, crowberry, wild blueberry/bilberry, blackberry, sour cherry, wild blackberry, wild strawberry, sunflower seed, cultivated blackberry and cowberry/cranberry.

The cereals containing most antioxidants included barley, common millet, maize and oats. Notably, polished rice and refined wheat, which are the main cereals eaten by humans globally (1,41), are among the cereals with the lowest content of antioxidants. In contrast, common millet and sorghum, which are important in particular regions in sub-Saharan Africa, South America and Asia (1,41), contained medium to high concentrations of antioxidants. Refining of all cereals results in substantial loss of FRAP activity.

A vegetable is any part of a plant not involved in the sexual reproduction of the plant. However, some botanically classified fruits, such as avocados, cucumbers, aubergines (eggplants), peppers, tomatoes and zucchini, are also treated as vegetables because of the culinary uses. Our analysis demonstrated that many vegetables, such as kale, chili pepper, red cabbage, pepper, parsley, artichoke, brussels sprouts and spinach, are also good sources of antioxidants. Vegetables contribute 8.9% of the total plant antioxidants in a Norwegian diet.

Fruits, which here exclude fruit vegetables and berries, also varied greatly in total antioxidant content. Fruits with the highest concentrations of antioxidants include pomegranate, grape, orange, plum, pineapple, lemon, date, kiwi, clementine and grapefruit. Fruits contribute 43.6% of the total plant antioxidants in a Norwegian diet. Orange and grapes are the most important sources among the fruits eaten in Norway.

Berries contained most of the high antioxidant dietary plants analyzed. Dog rose was exceptionally high, whereas other berries, including crowberry, wild blueberry, black currant, sour cherry, wild blackberry, wild strawberry, cultivated blackberry and cowberry/cranberry, also contained very high concentrations. Berries contribute 27.1% of the total plant antioxidants in a Norwegian diet. Strawberry, black currant and cranberry are the most important sources among the berries.

Of the dried fruits analyzed, apricots and prunes contained most antioxidants, 3.24 and 2.60 mmol/100 g, respectively. These values were two to six times the antioxidant values of the corresponding fresh fruits, suggesting that antioxidants are

TABLE 3

Total antioxidant concentrations of vegetables[1]

Vegetables	Botanical name	Family	Sample A[2]	*mmol/ 100 g*	Sample B	*mmol/ 100 g*	Sample C	*mmol/ 100 g*	Overall mean
Chilipepper	Capsicum annuum	Solanaceae	Holland ($n = 3$)[3]	2.08	Red, Spain ($n = 3$)	2.99	Green Spain ($n = 3$)	2.32	2.46
Kale/curly kale	Brassica oleracea var acephala	Brassicaceae	Bornick, Norway ($n = 3$)	2.65	USA ($n = 3$)	2.03			2.34
Red cabbage	Brassica oleracea var capitata, Rubra group	Brassicaceae	Autoro, Norway ($n = 3$)	2.09	Norway ($n = 3$)	1.77	Norway ($n = 3$)	1.79	1.88
Orange/yellow pepper	Capsicum anuum	Solanaceae	Orange, Holland ($n = 3$)	1.94	Yellow, Holland ($n = 3$)	1.84	Yellow, Holland ($n = 3$)	1.77	1.85
Parsley	Petroselinum crispum	Apiaceae	Norway ($n = 3$)	2.00	Norway ($n = 3$)	1.97	Mali ($n = 1$)	1.13	1.70
Artichoke, leaves	Cynara scolymus	Asteraceae	Italy ($n = 3$)	2.08	Italy ($n = 3$)	1.58	Italy ($n = 3$)	1.34	1.67
Red/green pepper	Capsicum anuum	Solanaceae	Red, Holland ($n = 3$)	1.81	Green, Holland ($n = 3$)	1.56	Green, Holland ($n = 3$)	1.55	1.64
Brussels sprout	Brassica oleracea var. gemmifera	Brassicaceae	Spain ($n = 3$)	1.31	Content, Norway ($n = 3$)	0.74	Spain ($n = 3$)	1.37	1.14
Spinach	Spinacia oleracea	Chenopodiaceae	Vikong290, Norway ($n = 3$)	1.10	Italy ($n = 3$)	0.96	Italy ($n = 3$)	0.87	0.98
Asparagus	Asparagus officinalis	Liliaceae	Agro Paracas, Peru ($n = 3$)	0.79	Agro Paracas, Peru ($n = 3$)	0.80	Agro Paracas, Peru ($n = 3$)	0.97	0.85
Celery	Apium graveolens	Apiaceae	Mali ($n = 3$)	0.80					0.80
Artichokes, heart	Cynaro scolymus	Asteraceae	Italy ($n = 3$)	0.71	Italy ($n = 3$)	0.67	Italy ($n = 3$)	0.69	0.69
Onion	Allium cepa	Liliaceae	Red, Italy ($n = 3$)	0.70	Yellow, Italy ($n = 3$)	0.63	Red Baron, Norway ($n = 3$)	0.67	0.67
Broccoli	Brassica oleracea var. italica	Brassicaceae	Norway ($n = 3$)	0.35	Spain ($n = 3$)	0.63	Spain ($n = 3$)	0.77	0.58
Leek	Allium porrum	Liliaceae	France ($n = 3$)	0.26	Mali ($n = 3$)	0.90	France ($n = 3$)	0.24	0.47
Okra	Hibiscus esculentis	Malvaceae	Mali ($n = 3$)	0.41					0.41
Avocado	Persea americana	Lauraceae	Spain ($n = 3$)	0.60	Israel ($n = 3$)	0.18	Spain ($n = 3$)	0.44	0.41
Savoy cabbage	Brassica oleracea var capitata, Subanda group	Brassicaceae	Taler, Norway ($n = 3$)	0.40	Norway ($n = 3$)	0.41	Norway ($n = 3$)	0.43	0.41
Radish	Raphanus sativus	Brassicaceae	France ($n = 3$)	0.39	France ($n = 3$)	0.42	Holland ($n = 3$)	0.39	0.40
Lettuce	Lactuca sativa	Asteraceae	Crispheaded, Norway ($n = 3$)	0.07	Lollo rosso, Norway ($n = 3$)	0.60			0.34
Tomato	Lycopersicon esculentum	Solanaceae	Cherry tomato, Holland ($n = 3$)	0.34	Plum tomato, Spain ($n = 3$)	0.24	Mali ($n = 2$)	0.34	0.31
Garlic, dried	Allium sativum	Liliaceae	Holland ($n = 3$)	0.24	USA ($n = 3$)	0.23	USA ($n = 3$)	0.24	0.24
Cauliflower	Brassica oleracea var. botrytis	Brassicaceae	Freemont, Norway ($n = 3$)	0.13	Alverda, Norway ($n = 3$)	0.22	Spain ($n = 3$)	0.35	0.23
Garlic	Allium sativum	Liliaceae	Holland ($n = 3$)	0.19	Senegal ($n = 3$)	0.25	Mali ($n = 3$)	0.18	0.21
Maize	Zea mays	Gramineae	Carmel, Israel ($n = 3$)	0.21	Spain ($n = 3$)	0.26	Mali ($n = 1$)	0.10	0.19
Aubergines/ eggplant	Solanum melongena	Solanaceae	Holland ($n = 3$)	0.25	Italy ($n = 3$)	0.18	Mali ($n = 2$)	0.07	0.17
Endive	Cichorium endivia	Asteraceae	France ($n = 3$)	0.10	France ($n = 3$)	0.08	France ($n = 3$)	0.11	0.10
Cabbage	Brassica oleracea var capitata, Capitata group	Brassicaceae	Norway ($n = 3$)	0.15	Lady, Norway ($n = 3$)	0.10	Mali ($n = 1$)	0.02	0.09
Squash	Cucurbita pepo	Cucurbitaceae	Green, Norway ($n = 3$)	0.11	Yellow, Spain ($n = 3$)	0.06	Mali ($n = 1$)	0.08	0.08
Fennel	Foeniculum vulgare	Apiaceae	Holland ($n = 3$)	0.07	Holland ($n = 3$)	0.06	Holland ($n = 3$)	0.09	0.07
Cucumber	Cucumis sativus	Cucurbitaceae	Russian ($n = 3$)	0.10	Norway ($n = 3$)	0.04	Mali ($n = 3$)	0.02	0.05
Zucchini/ courgettes	Cucurbita pepo	Cucurbitaceae	Mali ($n = 1$)	0.02					0.02

[1] Electron-donating antioxidants were determined by the FRAP assay. Values represent mean concentration per 100 g fresh weight of edible portion if not otherwise stated. The origin, brand and cultivar are indicated for each sample, if available.

[2] Samples A, B and C represent separate samples of the same dietary plant obtained from different sources such as geographical location or manufacturer.

[3] The number of items analyzed is indicated in parentheses.

TABLE 4

Total antioxidant concentrations of fruits[1]

Fruits	Botanical name	Family	Sample A[2]	*mmol/ 100 g*	Sample B	*mmol/ 100 g*	Sample C	*mmol/ 100 g*	Overall mean
Pomegranate	Punica granatum	Punicaceae	Spain (n = 3)[3]	11.33		0.00		0.00	11.33
Grape	Vitis vinifera	Vitaceae	Carmel, Israel (n = 3)	2.42	Chiquita, Chile (n = 3)	1.02	Del Monte, Chile (n = 3)	0.90	1.45
Orange	Citrus sinensis	Rutaceae	Spain	1.50	Outspan, Holland (n = 3)	1.08	Zenta (n = 3)	0.83	1.14
Plum	Prunus domestica	Rosaceae	Red beauty, Ciruella, Spain (n = 3)	1.42	Herman, Norway (n = 3)	1.02	Forlimpopoli, Italy (n = 3)	0.73	1.06
Pineapple	Ananas comosus	Bromeliaceae	Del Monte, Costa Rica (n = 3)	1.36	Ivory Coast (n = 3)	0.39	Del Monte, Costa Rica (n = 3)	1.36	1.04
Lemon	Citrus limon	Rutaceae	Dana, Spania (n = 3)	1.03	Dana, Spania (n = 3)	1.05	Dana, Spania (n = 3)	0.99	1.02
Date	Phoenix dactylifera	Arecaceae	USA (n = 3)	1.02	Mali (n = 3)	0.95	USA (n = 3)	1.10	1.02
Kiwi fruit	Actinida chinensis	Actinidiaceae	Yellow, Zespri, New Zealand (n = 3)	1.29	Green, Zespri, New Zealand (n = 3)	1.02	France (n = 3)	0.43	0.91
Clementine	Citrus reticulata	Rutaceae	Holland (n = 3)	0.99	Cevita (n = 3)	0.95	Gamma, Italy (n = 3)	0.75	0.90
Grapefruit	Citrus paradisii	Rutaceae	Red, Dole, Honduras (n = 3)	0.81	Yellow, Jaffa, Israel (n = 3)	0.82	Red, Dole, Honduras (n = 3)	0.87	0.83
Lime	Citrus aurantifolia	Rutaceae	Holland (n = 3)	0.73	Holland (n = 3)	0.75	Holland (n = 3)	0.72	0.73
Fig	Ficus carica	Moraceae	Smyrna, Turkey (n = 3)	0.81	Smyrna, Turkey (n = 3)	0.75	Smyrna, Turkey (n = 3)	0.64	0.73
Papaya	Carica papaya	Caricaceae	Mali (n = 1)	0.34	Dana, Brasil (n = 3)	0.75	Dana, Brasil (n = 3)	0.76	0.62
Apricot	Prunus armeniaca	Rosaceae	USA (n = 3)	0.52	USA (n = 3)	0.51	USA (n = 3)	0.52	0.52
Kaki/sharon	Diospyros kaki	Ebenaceae	Italy (n = 3)	0.54	Israel (n = 3)	0.33	Israel (n = 3)	0.42	0.43
Mango	Mangifera indica	Anarcadiaceae	Red, OJ, Pakistan (n = 3)	0.37	Red, Dole, Brasil (n = 3)	0.33	Yellow, La Bamba, Mexico (n = 3)	0.36	0.35
Apple	Malus pumila	Rosaceae	Golden Delicious, New Zealand (n = 3)	0.15	Granny Smith, New Zealand (n = 3)	0.51	Gala, Italy (n = 3)	0.22	0.29
Banana	Musa paradisiaca	Musaceae	Del Monte, Costa Rica (n = 3)	0.24	Mali (n = 1)	0.07	Del Monte, Costa Rica (n = 3)	0.29	0.20
Pear	Pyrus communis	Rosaceae	Holland (n = 3)	0.20	Holland (n = 3)	0.19	Norway (n = 3)	0.16	0.18
Plantain	Musa paradisiaca	Musaceae	Ivory Coast (n = 1)	0.17					0.17
Horned melon	Cucumis metuliferus	Cucurbitaceae	Kiviano, New Zealand (n = 3)	0.05	Pattern, Mali (n = 1)	0.15	Yellow, Mali (n = 1)	0.29	0.16
Cantaloupe melon	Cucumis melo	Cucurbitaceae	Rose, Spania (n = 3)	0.19	Brasil (n = 3)	0.13	Brasil (n = 3)	0.12	0.15
Watermelon	Citrullus lanatus	Cucurbitaceae	Red, Bouquet, Spain (n = 3)	0.06	Yellow, Bouquet, Spain (n = 3)	0.04	Mali (n = 1)	0.02	0.04

[1] Electron-donating antioxidants were determined by the FRAP assay. Values represent mean concentration per 100 g fresh weight of edible portion if not otherwise stated. The origin, brand and cultivar are indicated for each sample, if available.

[2] Samples A, B and C represent separate samples of the same dietary plant obtained from different sources such as geographical location or manufacturer.

[3] The number of items analyzed is indicated in parentheses.

relatively stable during the drying procedure used to produce these products. Dried figs contained about the same antioxidant concentrations as fresh figs. The antioxidant values of raisins were, however, much lower than the values for grapes, suggesting that antioxidants are lost during the drying procedure of this particular fruit. An alternative explanation could be that grape varieties with low concentrations of antioxidants are selectively used in raisin production.

An interesting feature that may be derived from our data is that the proportion of total antioxidants contributed by specific antioxidants, such as vitamin C, α-tocopherol, α-carotene, β-carotene, lutein, zeaxanthin and lycopene, is quite variable. Although these antioxidants combined contributed <25% of the FRAP values in most dietary plants, there are a few exceptions. One such exception is the carrot. Literature values for the five major carotenoids (α-carotene, β-carotene, lutein, zeaxanthin and lycopene) combined in carrots are ~120 mg/100 g (45), which corresponds to a FRAP value of 0.04 mmol/100 g. Because the actual FRAP concentration measured in carrots is 0.04 mmol/100 g (see Table 3), most of the antioxidants in carrots are apparently contributed by these five carotenoids. Another exception is kiwi, which typically contains ~0.4 mmol/100 g of vitamin C (46), which corresponds to a FRAP value of 0.8 mmol/100 g. Because our measured FRAP value for kiwi is 0.91 mmol/L, vitamin C apparently contributes most to the antioxidants in kiwi.

Three small-scale analyses of total antioxidants in dietary plants have been performed previously. By using the ORAC assay, Cao et al. (47) analyzed 22 vegetables and identified most antioxidants in garlic, followed by kale, spinach, brussels

TABLE 5

Total antioxidant concentrations of berries[1]

Berries	Botanical name	Family	Sample A[2]	*mmol/ 100 g*	Sample B	*mmol/ 100 g*	Sample C	*mmol/ 100 g*	Overall mean
Dog rose	Rosa canina	Rosaceae	Norway (n = 3)[3]	35.17	Norway (n = 3)	32.41	Norway (n = 3)	50.80	39.46
Crowberry	Empetrum hermaphroditum	Empetraceae	Norway (n = 3)	9.63	Norway (n = 3)	7.07	Norway (n = 3)	10.80	9.17
Blueberry/ bilberry, wild	Vaccinium myrtillus	Ericaceae	Poland (n = 3)	7.57	Norway (n = 3)	8.86	Sweden (n = 3)	8.25	8.23
Blackcurrant	Ribes nigrum	Grossulariaceae	Norway (n = 3)	5.49	Ben Tiran, Norway (n = 3)	9.09	Ben Tron, Norway (n = 3)	7.46	7.35
Strawberry, wild	Fragaria vesca	Rosaceae	Norway (n = 3)	7.01	Norway (n = 3)	6.67	Norway (n = 3)	6.95	6.88
Blackberry, wild	Rubus nemoralis	Rosaceae	Norway (n = 3)	5.83	Norway (n = 3)	6.40	Norway (n = 3)	6.17	6.13
Sour cherry	Prunus cerasus	Rosaceae	Norway (n = 3)	7.14	Poland (n = 3)	3.39	Norway (n = 3)	6.07	5.53
Blackberry, cultivated	Rubus fruticosus	Rosaceae	Findus, Norway (n = 3)	4.76	Belgium (n = 3)	3.84	Poland (n = 3)	6.61	5.07
Cowberry/ cranberry	Vaccinium vitis-idaea	Ericaceae	Poland (n = 3)	4.59	Norway (n = 3)	5.25	Norway (n = 3)	5.25	5.03
Elderberry	Sambucus nigra	Caprifoliaceae	Norway (n = 3)	5.24	Samdal, Norway (n = 3)	3.37			4.31
Raspberry, wild	Rubus idaeus	Rosaceae	Norway (n = 3)	4.01	Norway (n = 3)	3.96	Norway (n = 3)	3.93	3.97
Blueberry, cultivated	Vaccinum corymbosum	Ericaceae	Hardyblue, Norway (n = 3)	3.96	Aron, Norway (n = 3)	3.79	Patriot, Norway (n = 3)	3.17	3.64
Raspberry	Rubus idaeus ssp vulgatus	Rosaceae	Veten, Norway (n = 3)	3.35	Poland (n = 3)	3.35	Holland (n = 3)	2.49	3.06
Cloudberry	Rubus chamaemorus	Rosaceae	Norway (n = 3)	2.55	Norway (n = 3)	2.51	Sweden (n = 3)	3.44	2.83
Rowanberry	Sorbus aucuparia	Rosaceae	Norway (n = 3)	2.35	Norway (n = 3)	2.58	Norway (n = 3)	2.34	2.42
Strawberry, cultivated	Fragaria x ananassa	Rosaceae	Corona, Norway (n = 3)	2.34	Senga Sengana, Norway (n = 3)	1.85	Honeoy, Norway (n = 3)	2.33	2.17
Redcurrant	Ribes rubrum	Grossulariaceae	Norway (n = 3)	1.61	Poland (n = 3)	1.82	Poland (n = 3)	1.92	1.78
Gooseberries	Ribes uva-crispa	Grossulariaceae	Norway (n = 3)	1.45					1.45
Sweet cherry	Prunus avium	Rosaceae	USA, (n = 3)	0.62	Norway (n = 3)	1.42			1.02

[1] Electron-donating antioxidants were determined by the FRAP assay. Values represent mean concentration per 100 g fresh weight of edible portion if not otherwise stated. The origin, brand and cultivar are indicated for each sample, if available.

[2] Samples A, B and C represent separate samples of the same dietary plant obtained from different sources such as geographical location or manufacturer.

[3] The number of items analyzed is indicated in parentheses.

sprouts, alfalfa sprouts, broccoli flowers, beets, red bell pepper, onion, corn, eggplant, cauliflower, white potatoes, sweet potatoes, cabbage, leaf lettuce, string beans, carrot, yellow squash, iceberg lettuce, celery and cucumber. It is important to note that Cao et al. (47) used three different types of free radicals, that each type of free radical resulted in quit different hierarchies, and that the final hierarchy was established by calculating a total antioxidant score as the sum of the three datasets. When we compared our FRAP values with the ORAC values of similar items as determined by Cao et al. (47) (i.e., $ROO^{\bullet}$, $OH^{\bullet}$, and Cu^{++} generated free radical), we obtained the following correlation coefficients: 0.788, 0.681 and 0.132. The correlation coefficient between our dataset and the total antioxidant score of Cao et al. (47) was 0.790. Interestingly, garlic, which has the highest antioxidant activity by the ORAC assay, contained only 0.21 mmol total antioxidants per 100 g when analyzed in the FRAP assay. This discrepancy is most likely explained by the observation that garlic is especially enriched in sulfur-containing compounds (48) that are not detected by FRAP.

Wang et al. (49) analyzed total antioxidants in 12 fruits by the ORAC assay by using one type of free radical ($ROO^{\bullet}$) and obtained the following potencies (in ranked order): strawberry, plum, orange, red grapes, kiwi fruit, pink grapefruit, white grapes, banana, tomato, pear and melon. The correlation coefficient between our dataset and the data of Wang et al. (49) was 0.951.

Recently, Miller et al. (50) used 2,2-diphenyl-1-picrylhydrazyl as a stable free radical in a TEAC assay and analyzed total antioxidants in 20 vegetables, 15 fruits and 5 berries. The correlation coefficients between the dataset of Miller et al. (50) and our FRAP-based data were 0.468. Thus, it appears that care should be taken when using free radicals as the basis for generating an antioxidant activity, because the activity is very dependent on the specific free radical used (47). One should use different free radicals and calculate an antioxidant score as done by Cao et al. (47) or one should preferably use the FRAP assay, which is based on a much less selective reduction.

More data are needed on bioavailability and bioactivity, as well as the effect of processing and storage of the compounds identified in these assays. These assays represent, however, a first crucial step that should be followed up in future studies aiming at elucidating their function in the human body.

It is unlikely that antioxidants in dietary plants may explain all of the protective effect against oxidative stress-related chronic diseases. One additional defense mechanism that has been suggested involves the induction of detoxification enzymes, including members of the glutathione *S*-transferase family and NAD(P)H:quinone reductase (quinone reductase)

TABLE 6

Total antioxidant concentrations of pulses[1]

Pulses	Botanical name	Family	Sample A[2]	*mmol/ 100 g*	Sample B	*mmol/ 100 g*	Sample C	*mmol/ 100 g*	Overall mean
Broad bean/ fava bean	Vicia faba/faba vulgaris	Fabaceae	Green, Toko-sun, Holland ($n = 3$)[3]	1.94	Toko-sun, Holland ($n = 3$)	1.64	Green, Toko-sun, Holland ($n = 3$)	1.99	1.86
Pinto bean/ black bean	Phaseolus vulgaris	Fabaceae	S&W, USA ($n = 3$)	1.23	S&W, USA ($n = 3$)	1.04	S&W, USA ($n = 3$)	1.16	1.14
Ground nut/ peanut	Arachis hypogaea	Fabaceae	Pink, Kina ($n = 3$)	1.03	Pink, Kina ($n = 3$)	1.17	Mali ($n = 3$)	1.04	1.08
Soya beans	Glycine maximus	Fabaceae	Mekong, Thailand ($n = 3$)	0.91	Mekong, Thailand ($n = 3$)	0.74	Mekong, Thailand ($n = 3$)	0.81	0.82
Black-eyed pea/ bean	Vigna unguiculata ssp unguiculata	Fabaceae	GFT Darmstadt, Germany ($n = 3$)	0.47	Mekong, Thailand ($n = 3$)	0.79	Mekong, Thailand ($n = 3$)	0.69	0.65
Lentils	Lens culinaris	Fabaceae	Green, Tyrkey ($n = 3$)	1.00	Red, Tyrkey ($n = 3$)	0.23	Red, Tyrkey ($n = 3$)	0.23	0.49
Kidney beans	Phaseolus vulgaris ssp. vulgaris	Fabaceae	Toko-sun, Holland ($n = 3$)	0.41	Red, Conevas Viter, Spain ($n = 3$)	0.39	Toko-sun, Holland ($n = 3$)	0.33	0.38
Mung bean	Vigna radiata	Fabaceae	Toko-sun, Holland ($n = 3$)	0.33	Urd, India ($n = 3$)	0.36	Toko-sun, Holland ($n = 3$)	0.37	0.35
Chickpeas	Cicer arietinum	Fabaceae	Tyrkey ($n = 3$)	0.23	Tyrkey ($n = 3$)	0.24	Tyrkey ($n = 3$)	0.21	0.23
Garden pea	Pisum sativa ssp sativum	Fabaceae	Norway ($n = 3$)	0.09	Norway ($n = 3$)	0.10	Norway ($n = 3$)	0.16	0.12

[1] Electron-donating antioxidants were determined by the FRAP assay. Values represent mean concentration per 100 g fresh weight of edible portion if not otherwise stated. The origin, brand and cultivar are indicated for each sample, if available.
[2] Samples A, B and C represent separate samples of the same dietary plant obtained from different sources such as geographical location or manufacturer.
[3] The number of items analyzed is indicated in parentheses.

(51,52). These enzymes are generally referred to as phase 2-enzymes because they catalyze conversion of xenobiotics, mutagenic metabolites or their precursors to compounds that are more readily excreted. It is believed that if benign plant compounds induce the phase 2 enzymes, cells are more readily able to neutralize carcinogenic or toxic agents when they appear. Dietary plants enriched in compounds that induce phase 2 detoxification enzymes include members of several vegetable families, such as Cruciferae (broccoli, brussels sprouts, cabbage, kale, cauliflower), Leguminosae (green beans), Umbelliferae (carrots, celery), Zingerberaceae (ginger), Liliaceae (asparagus, green onions, leeks), Compositae (leaf lettuce) and Chenopodiaceae (spinach) (51,52). Thus, the dietary plants containing most antioxidants appear to belong to other plant species than those containing the best phase 2 enzyme inducers.

To summarize, our results demonstrated that there is more than a 1000-fold difference between total antioxidants in various dietary plants. Plants that contain most antioxidants included members of several families, such as Rocaceae (dog rose, sour cherry, blackberry, strawberry, raspberry), Empetraceae (crowberry), Ericaceae (blueberry), Grossulariaceae

TABLE 7

Total antioxidant concentrations of nuts and seeds[1]

Nuts and seeds	Botanical name	Family	Sample A	*nmol/ 100 g*	Sample B	*nmol/ 100 g*	Sample C	*nmol/ 100 g*	Overall mean
Walnut	Juglans regia	Juglandaceae	Diamond ($n = 3$)[2]	17.89	Helios ($n = 3$)	19.76	Helios ($n = 3$)	25.25	20.97
Sunflower seed	Helianthus annuus	Asteraceae	Natuvit, Danmark ($n = 3$)	5.41	Natuvit, Danmark ($n = 3$)	4.57	Natuvit, Danmark ($n = 3$)	6.18	5.39
Sesame seed	Sesamum indicum	Pedaliaceae	Natana, Danmark ($n = 3$)	1.09	Natana, Danmark ($n = 3$)	1.25	Natana, Danmark ($n = 3$)	1.28	1.21
Hazelnut	Corylus avellana	Betulaceae	Nøttefabrikken ($n = 3$)	0.48	Solbætorvet ($n = 3$)	0.50	Nøttefabrikken ($n = 3$)	0.49	0.49
Almond	Prunus amygdalus	Rosaceae	Solbætorvet ($n = 3$)	0.44	ICA, Norway ($n = 3$)	0.23	Meny, Norway ($n = 3$)	0.23	0.30
Cashew nut	Anacardium occidentale	Anarcadiaceae	Nøttefabrikken ($n = 3$)	0.22	Nøttefabrikken ($n = 3$)	0.23	Nøttefabrikken ($n = 3$)	0.24	0.23

[1] Electron-donating antioxidants were determined by the FRAP assay. Values represent mean concentration per 100 g fresh weight of edible portion if not otherwise stated. The origin, brand and cultivar are indicated for each sample, if available. Samples A, B and C represent separate samples of the same dietary plant obtained from different sources such as geographical location or manufacturer.
[2] The number of items analyzed is indicated in parentheses.

TABLE 8

Total antioxidant concentrations of dried fruits[1]

Dried fruits	Botanical name	Family	Sample A[2]	*mmol/ 100 g*	Sample B	*mmol/ 100 g*	Sample C	*mmol/ 100 g*	Overall mean
Apricot, dried	Prunus armeniaca	Rosaceae	Diva, Tyrkia ($n = 3$)[3]	3.27	Sunsweet, California ($n = 3$)	3.23	Diva, Tyrkia ($n = 3$)	3.23	3.24
Prune	Prunus nigra	Rosaceae	Diva, California ($n = 3$)	1.95	Sunsweet, California ($n = 3$)	2.17	Sunsweet, California ($n = 3$)	3.69	2.60
Raisins	Vitis vinifera	Vitaceae	SunMaid, USA ($n = 3$)	0.92	Asteche, Spania ($n = 3$)	0.92	Korints, USA ($n = 3$)	0.57	0.80
Fig, dried	Ficus carica	Moraceae	Smyrna, Italia ($n = 3$)	0.71	Smyrna, Italia ($n = 3$)	0.78	Smyrna, Italia ($n = 3$)	0.79	0.76

[1] Electron-donating antioxidants were determined by the FRAP assay. Values represent mean concentration per 100 g fresh weight of edible portion if not otherwise stated. The origin, brand and cultivar are indicated for each sample, if available.

[2] Samples A, B and C represent separate samples of the same dietary plant obtained from different sources such as geographical location or manufacturer.

[3] The number of items analyzed is indicated in parentheses.

(black currant), Juglandaceae (walnut), Asteraceae (sunflower seed), Punicaceae (pomegranate) and Zingiberaceae (ginger). With the data of this report, it is possible for the first time to make a comprehensive calculation of the total intake of antioxidants by an individual and to test the hypothesis that total dietary antioxidants have a protective role in oxidative stress-related pathogenesis.

LITERATURE CITED

1. World Cancer Research Fund/American Institute for Cancer Research (1997) Food, Nutrition and the Prevention of Cancer: A Global Perspective. American Institute for Cancer Research, Washington, DC.
2. U. S. Department of Agriculture, U. S. Department of Health and Human Services (1995) Nutrition and Your Health: Dietary Guidelines for Americans. U. S. Government Printing Office, Washington, DC.
3. American Heart Association (1996) Dietary guidelines for healthy American adults. Circulation 94: 1795–1800.
4. American Cancer Society (1996) Advisory committee on Diet, Nutrition and Cancer Prevention. Guidelines on diet, nutrition and cancer prevention: reducing the risk of cancer with healthy food choices and physical activity. CA. Cancer J. Clin. 46: 325–341.
5. World Health Organization (1990) Diet, Nutrition and the Prevention of Chronic Diseases: Report of a WHO Study Group—Technical Report Series 797. World Health Organization, Geneva, Switzerland.
6. Willett, W. C. (1999) Goals for nutrition in the year 2000. CA. Cancer. J. Clin. 49: 331–352.
7. Willett, W. C. (1998) Nutritional Epidemiology. Oxford University Press, New York, NY.
8. Jacobs, D. R., Jr., Marquart, L., Slavin, J. & Kushi, L. H. (1998) Whole-grain intake and cancer: an expanded review and meta-analysis. Nutr. Cancer 30: 85–96.
9. U. S. Department of Health and Human Services (1996) Physical Activity and Health: A Report of the Surgeon General. U. S. Government Printing Office, Atlanta, GA.
10. Beckman, K. B. & Ames, B. N. (1998) The free radical theory of aging matures. Physiol. Rev. 78: 547–581.
11. Ames, B. N., Shigenaga, M. K. & Hagen, T. M. (1993) Oxidants, antioxidants, and the degenerative diseases of aging. Proc. Natl. Acad. Sci. U.S.A. 90: 7915–7922.
12. Sies, H. (1997) Oxidative stress: oxidants and antioxidants. Exp. Physiol. 82: 291–295.
13. Gutteridge, J. M. & Halliwell, B. (2000) Free radicals and antioxidants in the year 2000: a historical look to the future. Ann. N. Y. Acad. Sci. 899: 136–147.
14. Halliwell, B. (1996) Antioxidants in human health and disease. Annu. Rev. Nutr. 16: 33–50.
15. Briviba, K., Klotz, L. O. & Sies, H. (1997) Toxic and signaling effects of photochemically or chemically generated singlet oxygen in biological systems. Biol. Chem. 378: 1259–1265.
16. Sen, C. K. & Packer, L. (1996) Antioxidant and redox regulation of gene transcription. FASEB J. 10: 709–720.
17. Halliwell, B. (1999) Antioxidant defence mechanisms: from the beginning to the end (of the beginning). Free Radic. Res. 31: 261–272.
18. Carr, A. & Frei, B. (1999) Does vitamin C act as a pro-oxidant under physiological conditions? FASEB J. 13: 1007–1024.
19. Sies, H. & Stahl, W. (1995) Vitamins E and C, β-carotene, and other carotenoids as antioxidants. Am. J. Clin. Nutr. 62: 1315S–1321S.
20. Packer, L., Weber, S. U. & Rimbach, G. (2001) Molecular aspects of α-tocotrienol antioxidant action and cell signaling. J. Nutr. 131: 369S–373S.
21. Halliwell, B. (2000) The antioxidant paradox. Lancet 355: 1179–1180.
22. McCall, M. R. & Frei, B. (1999) Can antioxidant vitamins materially reduce oxidative damage in humans? Free Radic. Biol. Med. 26: 1034–1053.
23. Albanes, D., Heinonen, O. P., Taylor, P. R., Virtamo, J., Edwards, B. K., Rautalahti, M., Hartman, A. M., Palmgren, J., Freedman, L. S., Haapakoski, J., Barrett, M. J., Pietinen, P., Malila, N., Tala, E., Liippo, K., Salomaa, E. R., Tangrea, J. A., Teppo, L., Askin, F. B., Taskinen, E., Erozan, Y., Greenwald, P. & Huttunen, J. K. (1996) α-Tocopherol and β-carotene supplements and lung cancer incidence in the α-tocopherol, β-carotene cancer prevention study: effects of base-line characteristics and study compliance. J. Natl. Cancer Inst. 88: 1560–1570.
24. Omenn, G. S., Goodman, G. E., Thornquist, M. D., Balmes, J., Cullen, M. R., Glass, A., Keogh, J. P., Meyskens, F. L., Valanis, B., Williams, J. H., Barnhart, S., Cherniack, M. G., Brodkin, C. A. & Hammar, S. (1996) Risk factors for lung cancer and for intervention effects in CARET, the β-Carotene and Retinol Efficacy Trial. J. Natl. Cancer Inst. 88: 1550–1559.
25. Omenn, G. S., Goodman, G. E., Thornquist, M. D., Balmes, J., Cullen, M. R., Glass, A., Keogh, J. P., Meyskens, F. L., Valanis, B., Williams, J. H., Barnhart, S. & Hammar, S. (1996) Effects of a combination of β-carotene and vitamin A on lung cancer and cardiovascular disease. N. Engl. J. Med. 334: 1150–1155.
26. Rapola, J. M., Virtamo, J., Ripatti, S., Huttunen, J. K., Albanes, D., Taylor, P. R. & Heinonen, O. P. (1997) Randomised trial of α-tocopherol and β-carotene supplements on incidence of major coronary events in men with previous myocardial infraction. Lancet 349: 1715–1720.
27. Verhagen, H., de Vries, A., Nijhoff, W. A., Schouten, A., Van Poppel, G., Peters, W. H. & Van den Berg, H. (1997) Effect of brussels sprouts on oxidative DNA-damage in man. Cancer Lett. 114: 127–130.
28. Verhagen, H., Poulsen, H. E., Loft, S., Van Poppel, G., Willems, M. I. & Van Bladeren, P. J. (1995) Reduction of oxidative DNA-damage in humans by brussels sprouts. Carcinogenesis 16: 969–970.
29. Lean, M.E.J., Noroozi, M., Kelly, I., Burns, J., Talwar, D., Sattar, N. & Crozier, A. (1999) Dietary flavonols protect diabetic human lymphocytes against oxidative damage to DNS. Diabetes 48: 176–181.
30. Boyle, S. P., Dobson, V. L., Duthie, S. J., Kyle, J.A.M. & Collins, A. R. (2000) Absorption and DNA protective effects of flavonoid glycosides from an onion meal. Eur. J. Nutr. 39: 213–223.
31. Van Poppel, G., Poulsen, H., Loft, S. & Verhagen, H. (1995) No influence of beta carotene on oxidative DNA damage in male smokers. J. Natl. Cancer Inst. 87: 310–311.
32. Halliwell, B. (1999) Vitamin C: poison, prophylactic or panacea? Trends Biochem. Sci. 24: 255–259.
33. Buettner, G. R. (1993) The pecking order of free radicals and antioxidants: lipid peroxidation, α-tocopherol and ascorbate. Arch. Biochem. Biophys. 300: 535–543.
34. Prior, R. L. & Cao, G. (2000) Antioxidant phytochemicals in fruits and vegetables: dietary and health implications. Hort. Sci. 35: 588–592.
35. Paganaga, G., Miller, N. & Rice-Evans, C. A. (1999) The polypohenolic content of fruit and vegetables and their antioxidant activities: what does a serving constitute? Free Radic. Res. 30: 153–162.
36. Miller, N. J. & Rice-Evans, C. A. (1996) Spectrophotometric determination of antioxidant activitry. Redox. Rep. 2: 161–168.
37. Benzie, I.F.F. & Strain, J. J. (1996) The ferric reducing ability of plasma (FRAP) as a measure of "antioxidant power": the FRAP assay. Anal. Biochem. 239: 70–76.

38. DeLange, R. J. & Glazer, A. N. (1989) Phycoerythrin fluorescence-based assay for peroxyl radicals: a screen for biologically relevant protective agents. Anal. Biochem. 177: 300–306.
39. Cao, G., Alessio, H. M. & Cutler, R. G. (1993) Oxygen-radical absorbance capacity assay for antioxidants. Free Radic. Biol. Med. 14: 303–311.
40. Schafer, F. Q. & Buettner, G. R. (2001) Redox environment of the cell as viewed through the redox state of the glutathione disulfide/glutathione couple. Free Radic. Biol. Med. 30: 1191–1212.
41. Davidson, A. (1999) The Oxford Companion to Food. Oxford University Press, Oxford, UK.
42. Norsk plantenomenklaturråd for hagebruk— Navn på frukt, bær og nøtter (Names of fruits, berries and nuts). (1993) Ed. E. Strømme. Faginfo/Statens fagtjeneste for landbruket. 1;15 Statens fagtjeneste for landbruket, Ås, Norway.
43. Norsk plantenomenklaturråd for hagebruk. (1993) Navn på grønnsaker og krydderplanter (Names of vegetables, herbs and spices). Ed. E. Strømme. Faginfo/Statens fagtjeneste for landbruket; 16. Ås, Norway: Statens fagtjeneste for landbruket.
44. National Nutrition Council (1998) The Norwegian Diet, Nutrition and Food Policy. National Nutrition Council, Oslo, Norway.
45. Mangels, A. R., Holden, J. M., Beecher, G. R., Forman, M. R. & Lanza, E. (1993) Carotenoid content of fruits and vegetables: an evaluation of analytical data. J. Am. Diet. Assoc. 93: 284–296.
46. Norwegian Food Composition Table. (1995) Universitetsforlaget, Oslo, Norway.
47. Cao, G., Sofic, E. & Prior, R. L. (1996) Antioxidant capacity of tea and common vegetables. J. Agric. Food Chem. 4: 3426–3431.
48. Milner, J. A. (2001) A historical perspective on garlic and cancer. J. Nutr. 131: 1027S–1031S.
49. Wang, H., Cao, G. & Prior, R. L. (1996) Total antioxidant capacity of fruits. J. Agric. Food Chem. 44: 701–705.
50. Miller, H. E., Rigelhof, F., Marquart, L., Prakash, A. & Kanter, M. (2000) Antioxidant content of whole grain breakfast cereals, fruits and vegetables. J. Am. Coll. Nutr. 19: 312S–319S.
51. Fahey, J. W., Zhang, Y. & Talalay, P. (1997) Broccoli sprouts: an exceptionally rich source of inducers of enzymes that protect against chemical carcinogens. Proc. Natl. Acad. Sci. U.S.A. 94: 10367–10372.
52. Talalay, P. (2000) Chemoprotection against cancer by induction of phase 2 enzymes. Biofactors 12: 5–11.