DOI: 10.1002/jsfa.2176

Daily consumption of phenolics and total antioxidant capacity from fruit and vegetables in the American diet

Ock Kyoung Chun,[1] Dae-Ok Kim,[1] Nancy Smith,[1] David Schroeder,[2] Jae Taek Han[3] and Chang Yong Lee[1]*

[1]*Department of Food Science and Technology, Cornell University, Geneva, NY 14456, USA*
[2]*Department of Food Science and Technology, University of Nebraska, Nebraska, NB 68588, USA*
[3]*Graduate School of Biotechnology and Plant Metabolism Research Center, Kyung Hee University, Suwon 449-701, Korea*

Abstract: The daily intake of total phenolics, total flavonoids and antioxidants in the American diet was estimated from the most common 34 fresh fruit and vegetables and their daily consumption data. Among 14 fruit and 20 vegetables, orange contributed the highest amount of total phenolics [117.1 mg gallic acid equivalent (GAE) person^{-1} day^{-1}] and antioxidants [146.6 mg vitamin C equivalents (VCE) person^{-1} day^{-1}]. Orange contributed about 26 and 25% of total phenolics and antioxidant, respectively, in the daily consumption of fruit and vegetables. Apples showed relatively high levels of total phenolics and antioxidant capacity comparable to those of oranges and their phenolics and antioxidants contribution is the second highest. Even though potatoes had lower levels of phenolics and antioxidant capacity, they were third due to the fact that their consumption is the highest (137.9 lb person^{-1} year^{-1}) in the American diet. Although plums and strawberries were ranked as the group with the highest total phenolics and antioxidant capacity among 34 tested fruit and vegetables, their contributions were relatively low due to their lower daily consumption. Generally, the levels of total phenolics, total flavonoids and antioxidant capacity of fruits were higher than those of vegetables. American daily intake of phenolics, flavonoids and antioxidants from fruits and vegetables was estimated to be 450 mg GAE, 103 mg catechin equivalents and 591 mg VCE, respectively. Although we do not yet know the required minimum daily amounts of antioxidants, when we estimate the daily requirement of antioxidants, we must consider not only the antioxidant concentrations of the particular food, but also the daily intakes of the food.

Keywords: fruits; vegetables; phenolics; flavonoids; vitamin C equivalent antioxidant capacity (VCEAC); daily food consumption

INTRODUCTION

High consumption of fruit and vegetables has proven to be associated with lower incidence and mortality rate of various degenerative diseases such as cancer,[1–3] cardiovascular disease,[4–6] and immune dysfunction[7] by several human cohort and case–control studies. In addition to the vitamins and minerals present in fruit and vegetables, phytochemicals such as flavonoids and other phenolics may contribute to the protective effects. Many of these phenolic phytochemicals have antioxidant capacity and may protect cells against the oxidative damage caused by free radicals.[8] Oxidative stress can cause oxidative damage to large biomolecules such as proteins, DNA and lipids, resulting in an increased risk of cancer and cardiovascular disease.[7] Flavonoids and their derivatives are the largest and most important group of plant phenolics,[9] and have shown various biological effects including inhibition of low-density lipoprotein (LDL) oxidation, inhibition of human immunodeficiency virus type 1 protease as well as antimicrobial and anticarcinogenic capacities.[10–13] To prevent or slow the oxidative damage induced by free radicals, therefore, sufficient amounts of phenols as antioxidants need to be consumed in foods.

It is estimated that one-third of all cancer deaths in the United States could be avoided through appropriate dietary modification.[14,15] Studies on antioxidants in reducing cancer risk reported that there was a lower risk with increased intake of fruit and vegetables.[16,17] Rimm *et al*[18] gave evidence that the intake of vegetables, fruit and cereal fiber decreased the risk of coronary heart disease among American males.

Therefore, the assessment of the phenolic content in the daily diet is essential to the strategy for

* Correspondence to: Chang Yong Lee, Department of Food Science and Technology, Cornell University, Geneva, NY 14456, USA
E-mail: cyl1@cornell.edu
(*Received 13 July 2004; revised version received 26 October 2004; accepted 14 December 2004*)
Published online 31 March 2005

promoting a phenol-rich diet. Kuhnau[19] reported the average daily intake of flavonoids in the USA as $1\,\mathrm{g\,day^{-1}}$ by spectrophotometric assay. Hertog *et al* reported that the average intake of major flavonoids (quercetin, kaempferol, myricetin, luteolin and apigenin) using HPLC analysis was $23\,\mathrm{mg\,day^{-1}}$ in the Dutch diet[20] and $12.9\,\mathrm{mg\,day^{-1}}$ in the USA.[5] Using a spectrophotometric assay, Vinson *et al*[21,22] reported that the average per capita consumption of total phenolics from fruits and vegetables in the USA was 255 and $218\,\mathrm{mg\,day^{-1}}$, respectively. These big differences resulted from the different analytical methods used, limitation of compounds identified and the confusion of total phenolics with total flavonoids by investigators. There have been few studies that have evaluated the total antioxidant content obtained from the daily food consumed in the USA.

Vinson *et al*[21,22] estimated the relative antioxidant capacity, measuring the concentration of phenols in the extract to inhibit 50% of the oxidation of LDL, and expressed the quality of antioxidants as IC_{50} values and phenol antioxidant index (PAOXI) based on molar unit. They determined the amount of total phenol and free phenol of each food extract obtained by heating for 2 or 3 h at 90 °C and also calculated the average daily per capita consumption of the total phenols from fruit and vegetables.

The illustration using Trolox, an unfamiliar artificial chemical to the public and/or molar unit expression of antioxidant capacity would widen even further the comprehension gap between general public and researchers and disturb intervention efficiency of dietary education for the prevention of chronic disease. Vitamin C is commonly recognized as a major, naturally occurring nutrient and antioxidant in diet. Therefore, vitamin C equivalent antioxidant capacity (VCEAC) on a weight basis ($\mathrm{mg\ 100\,g^{-1}}$) to show the antioxidant capacity of foods is more desirable.[23] There has been some research which has tried to express the antioxidant capacity of certain fruit as L-ascorbic acid equivalent;[24,25] however, they did not have any information on the total antioxidants obtained from the daily consumption of fruit and vegetables in the American diet.

The objectives of this study were to determine the content of total phenolics and total flavonoids of 34 fruit and vegetables commonly consumed in the USA, to calculate their antioxidant capacities using the expression of VCEAC and to determine the intake of total phenolics, total flavonoids and antioxidants from their daily consumption in America.

MATERIALS AND METHODS

Chemicals

2,2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid; ABTS) as diammonium salt, (+)-catechin, Folin–Ciocalteu's phenol reagent and gallic acid were purchased from Sigma Chemical Co (St Louis, MO, USA). Vitamin C was obtained from Fisher Scientific (Fair Lawn, NJ, USA). 2,2-Azobis(2-amidinopropane) dihydrochloride (AAPH) was obtained from Wako Chemicals USA Inc. (Richmond, VA, USA). All other chemicals used were of analytical grade (Fisher, Springfield, NJ, USA).

Samples

Fourteen fruits (apple, avocado, banana, cherry, grapefruit, grape, honeydew melon, kiwifruit, lemon, orange, peach, pear, plum and strawberry) and 20 vegetables (asparagus, bell pepper, broccoli, cabbage, carrot, cauliflower, celery, garlic, head lettuce, mushroom, onion, potato, pumpkin, radish, snap bean, spinach, squash, sweet corn, sweet potato and tomato) were analyzed in this study. Fresh samples used in this study were obtained from local supermarkets in Geneva, New York in 2002. After the samples were cleaned with tap water and dried, the edible portion was weighed, chopped, frozen and freeze-dried. Samples were ground to powder and then stored at −20 °C until analysis.

Food consumption and composition data

Annual per capita food consumption data for 2001 based on the prepared farm weight was obtained from the official internet web site of Economic Research Services (ERS), the United States Department of Agriculture (USDA).[26] We estimated the data for squash and pumpkins consumed in 2002 from personal communication with Gary Lucier, a researcher at ERS, USDA. The vitamin C content in fruit and vegetables was calculated from the National Nutrient Database, USDA[27] by averaging the vitamin C contents of different cultivars for each food item.

Extraction of phenolics

The phenolics in samples were extracted from 10 g of ground freeze-dried samples using 80% aqueous methanol in a 250 ml round-bottomed flask by the ultrasound-assisted method.[28] Methanol is a rapid, easy and efficient solvent for extracting phenolic phytochemicals from plant material because, compared with ethanol extraction, its low boiling point allows for rapid concentration of the extracted material. The mixture of sample powder and aqueous methanol was sonicated for 20 min with continuous nitrogen gas purging. The mixture was filtered and evaporated using a rotary evaporator under reduced pressure at 40 °C. The phenolic concentrate was dissolved in 50 ml of absolute methanol and then made up to the final volume of 100 ml with distilled deionized water (ddH_2O) obtained with a NANOpure water system (Barnstead, Dubuque, IA, USA). The solution was then centrifuged in a refrigerated superspeed centrifuge at $12\,000 \times g$ for 20 min. The final extract solution was stored at −20 °C until analysis. The phenolics of high fat samples, garlic (0.7%) and avocado (12.7%), were extracted directly without freeze-drying. Garlic and avocado were extracted with 200 g of 80%

aqueous methanol, homogenized, and centrifuged for 20 min. Homogenate was filtered, evaporated to near dryness in water bath at 45 °C, and diluted to 50 ml with ddH_2O. Extraction was done in duplicate.

Total phenolics and total flavonoids

Total phenolics were determined by the spectrophotometric method.[29] Appropriately diluted extracts (1 ml) were added to a 25 ml volumetric flask filled with 9 ml ddH_2O. A reagent blank using ddH_2O instead of sample was prepared. Folin–Ciocalteu phenol reagent (1 ml) was added to the mixture and mixed. After 5 min, 10 ml of 7% Na_2CO_3 solution were added with mixing. The solution was diluted to the volume (25 ml) with ddH_2O and then allowed to stand for 90 min, and the absorbance was measured at 750 nm vs the prepared blank. Total phenolic contents of sample were expressed on a fresh weight basis as mg of gallic acid equivalent (GAE) 100 g^{-1}. Samples of each extraction were analyzed in triplicate.

Total flavonoids were measured using a colorimetric assay developed by Zhishen *et al*.[30] Appropriately diluted extracts (1 ml) were added to a 10 ml volumetric flask filled with 4 ml ddH_2O. A reagent blank using ddH_2O instead of sample was prepared. Five minutes after the starting time, 0.3 ml 5% $NaNO_2$ was added to the flask, followed by 0.3 ml 10% $AlCl_3$. At 6 min, 2 ml of 1 M NaOH were added, diluted to volume (10 ml) with ddH_2O and then thoroughly mixed. During the reaction, a flavonoid–aluminum complex as a colored compound was formed. The color after the reaction is usually pink. The absorbance of the pink mixture was measured at 510 nm vs the prepared blank. Total flavonoids of samples were expressed on a fresh weight basis as mg catechin equivalent (CE) 100 g^{-1}. Samples were analyzed in triplicate.

Total antioxidant capacity expressed by VCEAC

The method described by Kim *et al*[23] was used in this study. One millimeter AAPH and 2.5 mM ABTS solutions were made up in 100 ml phosphate-buffered saline (PBS) solution [100 mM potassium phosphate buffer (pH 7.4) containing 150 mM NaCl]. After the mixture was heated in a water bath at 68 °C, the blue-green ABTS radical solution was adjusted with fresh PBS solution to an absorbance of 0.650 ± 0.020 at 734 nm. The sample solution (20 µl) was added to 980 µl ABTS radical solution and incubated in a water bath at 37 °C for 10 min. The decrease of absorbance at 734 nm was measured for 10 min. A control consisted of 20 µl of 50% aqueous methanol and 980 µl of ABTS radical solution. The ABTS radical scavenging capacities of sample extracts were expressed on the fresh weight basis as mg vitamin C equivalent 100 g^{-1} (VCEAC). Samples were analyzed in triplicate.

Intake estimation of total phenolics, flavonoids and antioxidants

The total phenolic intake obtained from daily food consumption was estimated from food consumption and total phenolic content as:

$$\begin{array}{c}\text{Total phenolics intake from vegetables}\\ \text{and fruits (mg GAE person}^{-1}\text{ day}^{-1}\text{)}\end{array} = \sum C_i P_i$$

where C_i is the food consumption for the selected fruit or vegetable (g food person^{-1} day^{-1})[26] and P_i is the total phenolics for the selected commodity (mg GAE 100 g food^{-1}).

The total flavonoids intake obtained from daily food consumption was estimated from food consumption and total flavonoid content as:

$$\begin{array}{c}\text{Total flavonoid intake from vegetables}\\ \text{and fruits (mg CE/person/day)}\end{array} = \sum C_i F_i$$

where F_i is the total flavonoid content for the selected commodity (mg CE 100 g food^{-1}).

The total antioxidant intake obtained from daily food consumption was estimated from food consumption and their antioxidant capacities as:

$$\begin{array}{c}\text{Total antioxidant intake from vegetables}\\ \text{and fruits(mg VCE person}^{-1}\text{ day}^{-1}\text{)}\end{array} = \sum C_i V_i$$

where V_i is the antioxidant capacity for the selected commodity (mg VCE 100 g food^{-1}).

RESULTS AND DISCUSSION

The total daily intake of total phenolics, flavonoids and antioxidants was estimated from the 34 commonly consumed fruit and vegetables and their daily consumption data. Tables 1 and 2 show the daily consumption of individual fruit and vegetables on the prepared farm weight basis. The food consumption data of fruit and vegetables used in this study were the sum of fresh and processed amounts and covered 87% of American daily fruit and vegetable consumption based on the USDA database.[26]

Total phenolics and flavonoids

Table 1 shows per capita consumption and the contents of total phenolics in 14 common fruits. Plums exhibited the highest content of total phenolics with 368.66 mg GAE 100 g^{-1} fresh sample, followed by strawberries, grapefruits, apples, bananas, oranges, lemons, peaches, green seedless grapes, pears, kiwifruit, avocados, cherries and honeydew melon. The relatively high total phenolic content in plums[29,31,32] and strawberries[33] was reported in previous studies. The total phenolic content of plums was much higher than that reported by Gil *et al*[24] on several plums cultivated in California (42.0 to 109.2 mg 100 g^{-1}) and a little higher than that of Kim *et al*[29] on six plum cultivars in 2000 from New York (173.9–374.6 mg 100 g^{-1}). Vinson *et al*[22] reported

Table 1. The level of total phenolics, total flavonoids and antioxidant capacity of fruit based on fresh weight

Fruits	Food consumption (per capita) lb year^{-1} [a]	g day^{-1}	Total phenolics mg GAE[b] 100 g^{-1}	Total flavonoids mg CE[b] 100 g^{-1}	Antioxidant capacity mg VCE[b] 100 g^{-1}
Apples	43.4	53.9	118.30 ± 1.40	62.00 ± 6.90	205.40 ± 5.60
Avocados	2.2	2.7	58.27 ± 1.63	33.62 ± 1.02	86.38 ± 4.94
Bananas	26.6	33.1	112.79 ± 6.70	34.17 ± 0.84	173.57 ± 5.21
Cherries	1.7	2.1	55.77 ± 2.94	43.84 ± 1.30	139.82 ± 5.52
Grapefruit	12.8	15.9	161.72 ± 7.66	5.07 ± 0.82	123.88 ± 25.00
Grapes	18.3	22.7	83.59 ± 4.35	24.03 ± 0.55	72.33 ± 23.61
Honeydew melon	2.0	2.5	11.45 ± 0.05	0.63 ± 0.13	17.52 ± 1.09
Kiwifruit	0.6	0.7	61.21 ± 1.82	7.30 ± 0.91	110.98 ± 5.27
Lemons	6.5	8.1	108.78 ± 6.72	47.63 ± 1.95	228.50 ± 22.81
Oranges	83.9	104.3	112.29 ± 4.50	11.82 ± 3.26	140.58 ± 41.86
Peaches	9.4	11.7	98.56 ± 3.66	22.12 ± 0.66	142.89 ± 7.75
Pears	6.1	7.6	70.19 ± 1.33	41.98 ± 2.43	105.80 ± 5.06
Plums	2.9	3.6	368.66 ± 12.66	194.42 ± 9.87	481.43 ± 15.03
Strawberries	5.8	7.2	225.00 ± 2.60	51.3 ± 1.40	347.20 ± 9.10

[a] USDA, Economic Research Service, 2000, July. The data were the sum of fresh and processed amount on the farm weight basis.
[b] Each value is the mean±SD ($n = 6$). GAE, gallic acid equivalent; CE, catechin equivalent; VCE, vitamin C equivalent.

Table 2. The level of total phenolics, total flavonoids and antioxidant capacity of vegetables based on fresh weight

Vegetables	Food consumption (per capita) lb year^{-1} [a]	g day^{-1}	Total phenols mg GAE[b] 100 g^{-1}	Total flavonoids mg CE[b] 100 g^{-1}	Antioxidant capacity mg VCE[b] 100 g^{-1}
Asparagus	1.2	1.5	64.15 ± 2.46	7.66 ± 0.31	82.78 ± 0.75
Bell peppers	6.7	8.3	52.49 ± 1.07	1.12 ± 0.09	64.91 ± 1.39
Broccoli	7.6	9.4	25.02 ± 0.85	2.35 ± 0.08	30.53 ± 1.24
Cabbage	10.3	12.8	45.28 ± 1.17	1.20 ± 0.18	58.51 ± 2.52
Carrots	14.0	17.4	8.40 ± 0.12	1.07 ± 0.09	11.25 ± 0.44
Cauliflower	2.1	2.6	10.40 ± 0.06	1.54 ± 0.05	16.39 ± 0.43
Celery	6.6	8.2	17.09 ± 1.56	0.28 ± 0.02	13.41 ± 0.41
Garlic	2.4	3.0	47.66 ± 2.16	5.43 ± 0.08	49.98 ± 0.53
Lettuce(head)	23.5	29.2	9.82 ± 0.27	4.57 ± 0.17	12.65 ± 0.44
Mushrooms	3.9	4.8	11.25 ± 0.31	1.06 ± 0.04	14.87 ± 0.27
Onions	18.9	23.5	24.27 ± 0.26	4.73 ± 0.21	21.76 ± 0.09
Potatoes	137.9	171.4	35.28 ± 0.56	6.63 ± 0.80	35.45 ± 2.05
Pumpkin[e]	4.9	6.1	15.93 ± 0.57	0.84 ± 0.07	20.81 ± 2.42
Radishes	0.5	0.6	29.45 ± 0.64	1.36 ± 0.03	39.27 ± 1.70
Snap beans	7.8	9.7	4.51 ± 0.16	0.66 ± 0.03	1.92 ± 0.04
Spinach	2.0	2.5	32.54 ± 0.35	1.42 ± 0.19	35.16 ± 2.38
Squash[c]	4.4	5.5	12.10 ± 0.18	0.42 ± 0.05	17.39 ± 1.18
Sweet corn	27.3	33.9	50.37 ± 1.27	5.03 ± 0.40	72.97 ± 3.11
Sweet potatoes	4.4	5.5	33.60 ± 1.02	5.84 ± 0.22	33.19 ± 2.13
Tomatoes	82.9	103.0	23.69 ± 0.21	1.77 ± 0.09	29.44 ± 1.60

[a] USDA, Economic Research Service, 2001, July. The data were the sum of fresh and processed amount on the farm weight basis.
[b] Each value is the mean±SD ($n = 6$). GAE, gallic acid equivalent; CE, catechin equivalent; VCE, vitamin C equivalent.
[c] Data estimated in 2002 (personal communication, Gary Lucier, USDA).

that grapes, bananas, cherries and plums exhibited high total phenolics, but the amounts of total phenolics of lemons, oranges, peaches, plums and strawberries were relatively lower than our results in this study. The differences from the results from the present study may be mainly attributed to different varieties of fruits used in the experiment and the different sample extraction method used. Vinson *et al*[22] extracted total phenolics of each fruits by heating for 2 or 3 h at 90 °C, while we used ultrasound-assisted extraction for 40 min at 40 °C in this study. Extraction efficiencies may be different according to the structures of plant tissues and characteristics of tissue components.[34]

Table 2 exhibits the total phenolic content of 20 common vegetables. Asparagus showed the highest content of total phenolics of 64.15 mg GAE 100 g^{-1} fresh sample, followed by bell pepper, sweet corn, garlic, cabbage, potatoes, sweet potatoes, spinach, radishes, broccoli, onion, tomatoes, celery, pumpkin, squash, mushroom, cauliflower, lettuce (head), carrots and snap beans. Vinson *et al*[21] reported that garlic, sweet corn, broccoli, sweet potatoes and asparagus exhibited relatively high total phenolic content, and potatoes had the lowest total phenol content among vegetables.

The estimated amounts of total phenolics from daily fruit and vegetable consumption examined in this study were 320.4 and 129.4 mg GAE, respectively. Vinson *et al*[21] reported that the average per capita consumption of phenols in fruit and vegetables was 255 and 218 mg CE, respectively. In addition, the source of food consumption data used in this study can partly account for the higher amount of estimated total phenolics than obtained by Vinson *et al*[21,22] results. In the present study, we used the USDA database based on food disappearance data and calculated on the prepared farm weight. We chose this database because it may provide the total consumption of oranges and apples, which are mainly consumed in the form of fruit juices. The estimated total phenolic intake of oranges was 117.1 mg GAE day^{-1} $person^{-1}$ and it was much higher than Vinson *et al*'s results[22] owing to the higher total phenolic content and higher daily consumption.

Tables 1 and 2 show the total flavonoids of 14 fruit and 20 vegetables. It showed a different tendency with the total phenolics in ranking: plums > apples > strawberries > lemons > cherries > pears > bananas > avocados > green seedless grapes > peaches > oranges > kiwifruits > grapefruits > honeydew melon in fruit; and asparagus > potatoes > sweet potatoes > garlic > sweet corn > onions > head lettuce > broccoli > tomatoes > cauliflower > spinach > radishes > cabbages > bell peppers > carrots > mushrooms > pumpkin > snap beans > squash > celery in vegetables. These differences can be explained as the different compositions and amounts of phenols in fruit and vegetables.

Recent studies have emphasized the importance and putative modes of action of specific flavonoids as bioactive components of diet in *in vivo* and *in vitro* models. Thus, it is more important to have an idea of the major phenolic families, which fruit and vegetables comprise than the total flavonoid contents. Proteggente *et al*[33] classified regularly consumed fruit and vegetables according to the major phenols: strawberries, cherries and plums are anthocyanin-rich fruit; oranges, lemons and grapefruit are flavanone-rich fruits; onions, leeks, green grapes, lettuce, broccoli, spinach and cabbage are flavonol-rich fruit and vegetables; and apples, pears, peaches and tomatoes are hydroxycinnamate-rich fruit and vegetables. In this study, anthocyanin-rich plums and strawberries showed relatively high total flavonoid contents among fruit samples. The average total flavonoid content of fruit and vegetables was 41.42 and 2.75 mg CE $100\,g^{-1}$, respectively. The flavonoid intakes (per day per capita) from fruit and vegetable consumption were 85.6 and 17.8 mg CE, respectively. This big gap can be explained as the contribution of flavonoids in total phenols of fruit being much more than that in vegetables.

Total antioxidant capacity expressed by VCEAC

The total antioxidant capacity of the 14 common fruits is shown in Table 1. Similarly to the result of total phenolics, plums showed the highest antioxidant capacity with 481.43 mg VCE, followed by strawberries, lemons, apples, bananas, peaches, oranges, cherries, grapefruits, kiwifruit, pears, avocado, green seedless grapes and honeydew melon. The average antioxidant capacity in 14 fruits was 169.73 mg VCE, which was similar to that of Leong and Shui,[25] where strawberries and plums showed the highest antioxidant capacity expressed as L-ascorbic acid equivalent antioxidant capacity and honeydew was the lowest. Vinson *et al*[22] reported that the antioxidant capacity of strawberries was the highest and that of honeydew melon was the lowest, and plums exhibited lower antioxidant capacity than grapes and cherries. The antioxidant capacities in fruit and vegetables may be influenced by cultivars, geographic origin, growing seasons, agricultural practices, substrate systems and analytical methods. Previous studies showed that the antioxidant capacities of red fruits were relatively much higher than those of the other fruits.[22,25,33,35–38] It can be explained that anthocyanins in red fruits are strong contributors to the total antioxidant capacity of fruits.[31] Halvorsen *et al*[39] reported a more than 1000-fold difference among total antioxidants in various dietary plants popularly consumed in Norway, and that berries exhibited the highest antioxidant capacity among foods tested.

Antioxidant capacities of fruit examined in this study might partly come from the vitamin C present in fruit. Wang *et al*,[40] however, reported that the contribution of vitamin C to the total antioxidant capacity of a fruit was usually less than 15%, except for kiwi fruit and honeydew melon. This suggests that the major source of antioxidant capacity of most fruit and commercial fruit juices may not be from vitamin C.

Table 2 shows the antioxidant capacity of 20 vegetables commonly consumed in the American diet. Asparagus showed the highest antioxidant capacity with 82.78 mg VCE $100\,g^{-1}$, followed by sweet corn, bell peppers, cabbage, garlic, radishes, potatoes, spinach, sweet potatoes, broccoli, tomatoes, onions, pumpkin, squash, cauliflower, mushrooms, celery, head lettuce, carrots and snap beans. Peppers have been reported to be rich in phenols as well as vitamins A and C, which are good sources of antioxidants.[41,42] Cao *et al*[43] reported that garlic, spinach, broccoli, red bell pepper and sweet corn exhibited high antioxidant capacities among the common vegetables. Sweet corn and cabbage in present study were good sources of antioxidants owing to their high VCEAC and high daily consumption. Previous studies[44,45] reported that garlic has antioxidant, antiatherosclerosis and anticancer capacity. In this study, garlic showed an antioxidant capacity of 50.0 mg VCEAC day^{-1} $person^{-1}$.

Proteggente *et al*[33] reported that fruit and vegetables rich in anthocyanins demonstrated the highest antioxidant capacities, followed by those rich in flavanones and flavonols, while the hydroxycinnamate-rich fruits consistently elicited the lower antioxidant capacities. In this study, orange and grapefruit, both rich in flavanones, had much lower antioxidant capacity than plums and strawberries.

Intake estimation of total phenolics, total flavonoids and antioxidants

Potatoes were the major food consumed at 171.4 g day^{-1} $person^{-1}$, followed by oranges, tomatoes, apples, sweet corn, bananas and head lettuce. The total phenolic intake obtained from daily food consumption was estimated from food consumption and total phenolic content. Figure 1 shows the total phenolics from daily consumption of fruit and vegetables. Oranges exhibited the highest total phenolic intake with 117.1 mg GAE among all the daily consumed fruit and vegetables, followed by apples, potatoes, bananas, grapefruit and tomatoes. Although plums showed the highest total phenolics on a fresh sample basis, the total phenolic intake was relatively low (13.3 mg GAE) due to the low daily consumption. On the other hand, potatoes showed the third highest total phenolic contribution owing to their high daily consumption. No matter how high the concentration of a certain bioactive compound is in a food, if the amount of that food consumed is low, the contribution of the bioactive compound in the diet could be low. Previous studies showed different aspects of the major contributor to the total phenolics in daily food consumption. Vinson *et al*[21,22] reported that banana (81.8 mg day^{-1}) was the highest total phenol provider among the daily consumed fruits and vegetables, followed by apple (57.1 mg day^{-1}), tomato (41.7 mg day^{-1}) and sweet corn (37.0 mg day^{-1}). Hertog *et al*[5] reported that onion was the leading vegetable source of five flavonoids measured by HPLC analysis in the American diet. However, the study was limited to only a few flavonoids and could not express the total phenolics existing in the vegetables. Vinson *et al*[21] suggested that tomato was first in the vegetables, which was second to potato in the present study. The different results from the present study may be due to the different extraction method, sample variation used in total phenolic content analysis and source of food consumption data used for estimation.

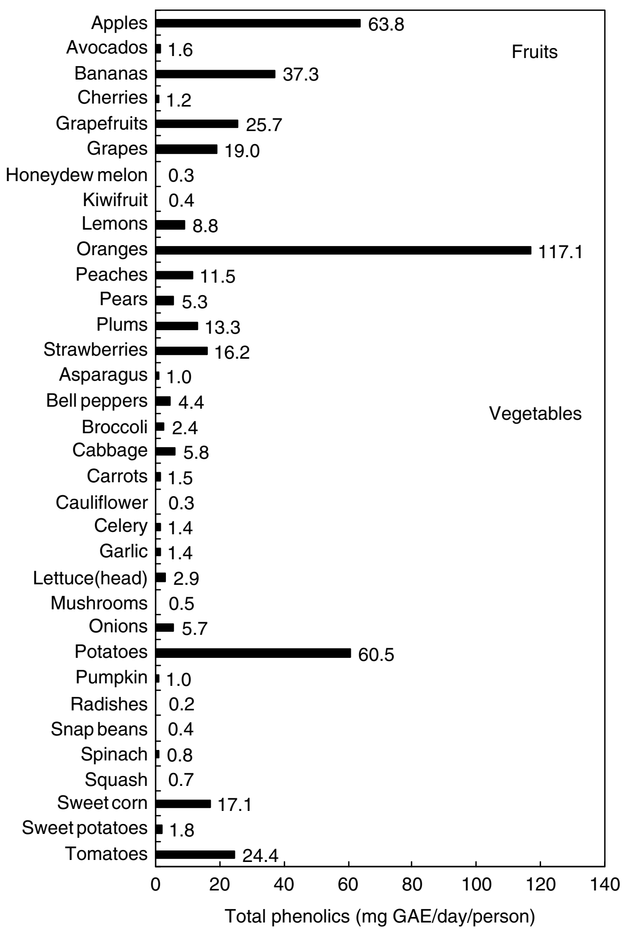

Figure 1. Comparison of total phenolics from daily consumption of fruit and vegetables.

Figure 2 shows the antioxidant provided by daily consumption of fruit and their antioxidant capacities in fresh status. Oranges exhibited the highest antioxidant amount of 146.6 mg VCE and they covered 33% of total antioxidants obtained from daily fruit consumption. The antioxidant intake showed almost the same tendency as the total phenolic intake. However, in the case of apples, the amount of antioxidants obtained from apple consumption increased to 25% owing to their higher antioxidant capacity than oranges. Although plums and strawberries showed very high antioxidant capacity on a fresh sample basis, the amount of antioxidants from these two fruits was relatively low due to low daily consumption.

Figure 3 shows which vegetables provide antioxidants from daily consumption and their antioxidant capacities in fresh status. Potatoes had the highest antioxidant amount with 60.8 mg VCE and they covered 40% of total antioxidants obtained from daily vegetable consumption. Potatoes exhibited much lower antioxidant capacity than asparagus or sweet corn, however, they could show the highest antioxidant intake owing to high daily consumption. Tomatoes (30.3 mg VCE) exhibited the second highest antioxidant intake due to their high daily consumption, although their antioxidant capacity was not high among the tested vegetables. Sweet corn (24.8 mg VCE) exhibited high antioxidant intake owing to its fairly high antioxidant capacity and a high daily consumption. Asparagus and bell peppers were proved to contribute relatively little by to the total antioxidant intake due to their low daily consumption, although they showed the highest antioxidant capacity among

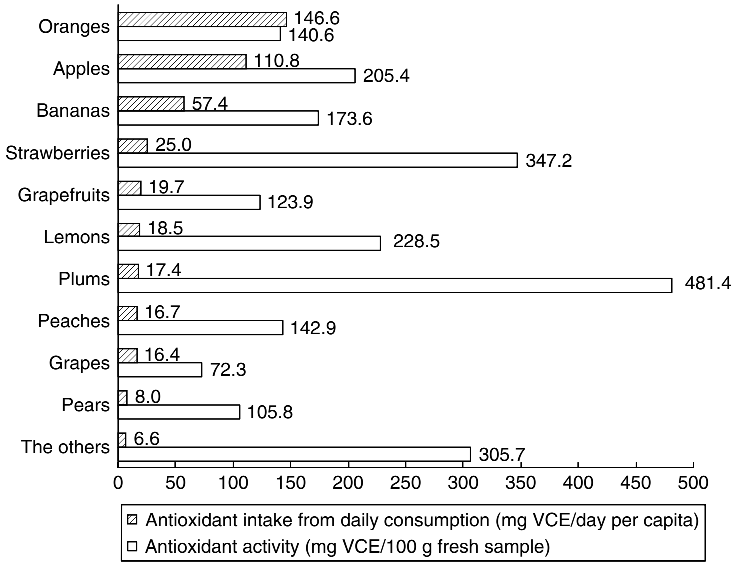

Figure 2. Comparison of antioxidant intakes from daily fruit consumption and antioxidant capacities in fresh samples.

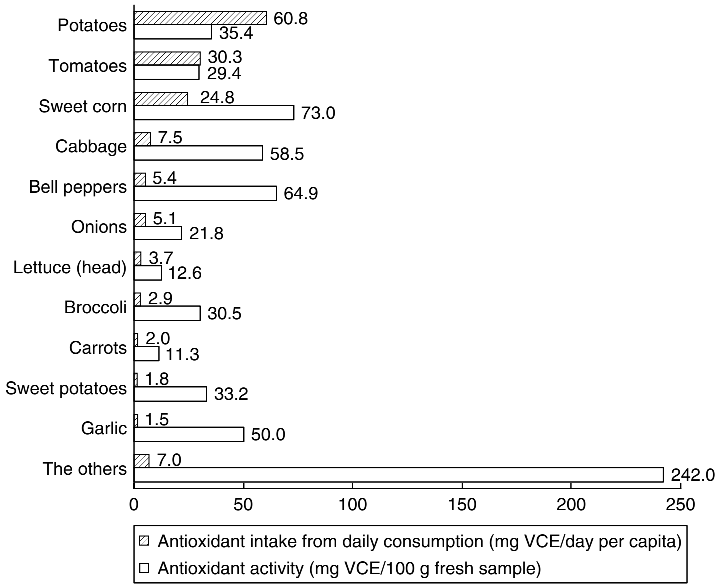

Figure 3. Comparison of antioxidant intakes from daily vegetable consumption and antioxidant capacities in fresh samples.

vegetables. Several studies demonstrated the antioxidant capacity of fruit and vegetables using total phenol antioxidant index (PAOXI),[21,22] the autoxidation of linoleic acid[46] and β-carotene bleaching capacity coupled with the oxidation of linoleic acid.[47] The results, however, showed different aspects of the antioxidant capacities according to the assay applied.

Figure 4 shows the estimation of daily total phenolics, flavonoids, and antioxidant intake from fruits and vegetables. The intake of total phenolics, total flavonoids and antioxidant from fruit was higher than that from vegetables. Owing to the higher consumption of vegetables, however, the gap in phenolics and antioxidant capacity uptake from fruit and vegetables was much less than the content on a fresh sample basis. From Fig 4, we can estimate the total intake of total phenolics, total flavonoids and antioxidant from daily consumption of fruit and vegetables as 450 mg GAE, 103 mg CE and 591 mg VCE, respectively. The total phenolic intake calculated in the present study was much lower than of Kuhnau (1 g day^{-1})[19] and higher than of Hertog *et al* (12.9 mg/day),[5] which were based on different analysis from this study. Although the estimation was different in each fruit and vegetable, Vinson *et al* (473 mg day^{-1})[21,22] showed a good accordance in the total phenolics consumed from the daily American diet with present study. In addition to fruit and vegetables, black and green teas, red wine and cocoa are rich in phenolic phytochemicals, and important sources of antioxidants in the diet.[43,48,49] Our previous study[48] reported that cocoa contained much higher levels of total phenolics (611 mg GAE) and flavonoids (564 mg of epicatechin equivalents, ECE) per serving than black tea (124 mg of GAE and 34 mg of ECE, respectively), green tea (165 mg

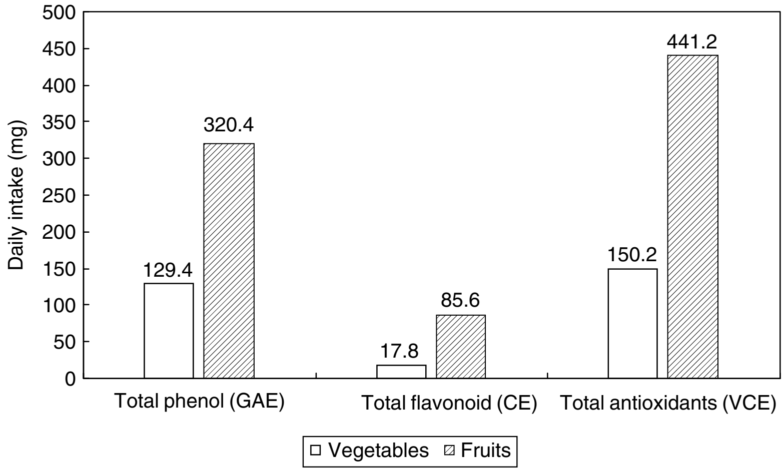

Figure 4. Estimation of total phenolics, total flavonoids, and total antioxidants intakes from daily consumption of fruit and vegetables. GAE, gallic acid equivalent; CE, catechin equivalent; VCE, vitamin C equivalent.

Table 3. The nutrient levels of fruits and vegetables based on a serving size

	Conventional serving size (g)	Total calories	Calories from fat	Total fat (g)	Dietary fiber (g)	DV[a] vitamin A (%)	DV[a] vitamin C (%)	VCEAC (mg VCE)
Apples	154	80	0	0	5	2	8	316
Asparagus	93	25	0	0	2	10	15	77
Avocados	30	55	45	5	3	0	4	26
Bananas	126	110	0	0	4	0	15	219
Bell peppers	148	30	0	0	2	8	190	96
Broccoli	148	45	0	0.5	5	15	220	45
Cabbage	84	25	0	0	2	0	70	49
Carrots	78	35	0	0	2	270	10	9
Cauliflower	99	25	0	0	2	0	100	16
Celery	110	20	0	0	2	2	15	15
Cherries	140	90	0	0.5	3	2	15	196
Grapefruit	154	60	0	0	6	15	110	191
Grapes	138	90	10	1	1	2	25	100
Honeydew melon	134	50	0	0	1	2	45	24
Kiwifruit	148	100	10	1	4	2	240	164
Lemons	58	15	0	0	1	0	40	132
Lettuce(head)	89	15	0	0	1	4	6	11
Mushrooms	84	20	0	0	1	0	2	13
Onions	148	60	0	0	3	0	20	32
Oranges	154	70	0	0	7	2	130	217
Peaches	98	40	0	0	2	2	10	140
Pears	166	100	10	1	4	0	10	176
Plums	132	80	10	1	2	6	20	636
Potatoes	148	100	0	0	3	0	45	53
Radishes	85	15	0	0	0	0	30	33
Snap beans	83	25	0	0	3	4	10	2
Spinach	85	40	0	0	5	70	25	30
Squash	98	20	0	0	2	6	30	17
Strawberries	147	45	0	0	4	0	160	510
Sweet corn	90	80	10	1	3	2	10	66
Sweet potatoes	130	130	0	0	4	440	30	43
Tomatoes	148	35	0	0.5	1	20	40	44

[a] Percentage daily values (DV) are based on a 2000 calorie diet. Daily values may be higher or lower depending on energy needs.
Source: US Food and Drug Administration and Produce Marketing Association.[47]

GAE and 47 mg ECE), and red wine (340 mg GAE and 163 mg ECE), and that they all exhibited high antioxidant capacities per serving. Therefore, if we include beverages in estimates, the intakes of total phenolics, flavonoids and antioxidants will be much higher than our estimates.

Several studies reported that some common fruits have high antioxidant capacities, which cannot be accounted for by their vitamin C content,[37] and some flavonoids have much stronger antioxidant capacities against peroxylradicals than vitamin E, vitamin C and glutathione.[50]

It was suggested that combination of fruit phytochemicals resulted in antioxidant capacity that was additive and synergistic.[35] The benefits of a diet rich in fruit and vegetables is attributed to the complex mixture of phytochemicals present in whole foods.[51] Food are very complex by nature and interactions among foods and their constituents, such as fiber, nutrients and phytonutrients, strengthen their health-promoting abilities.[52] Thus, balanced natural combinations of phytochemicals present in fruits and vegetables cannot be simply mimicked by expensive nutritional supplements.[53]

Table 3 shows nutritional level intake from single servings of fruit and vegetables. As seen in this table, plums, strawberries and apples are very excellent sources of fiber, vitamin A, vitamin C and various antioxidants. To change dietary behavior and get people to eat five to nine servings of fruit and vegetables daily, depending on their energy needs, we need to work together as health professionals to interpret the science and make strong policy and program decisions based on that science. Not all foods are created equal. Some are more nutritious than others. A good way to raise the intake of antioxidants from fruit and vegetables is to increase the proportion of consumption, and another effective way is to substitute the fruit and vegetables that have low antioxidant capacity with antioxidant-rich fruit and vegetables. In addition, a colorful variety of all fruit and vegetables, healthfully prepared, makes a significant contribution to a diet that promotes good health.[52]

CONCLUSION

Overall, it can be concluded that fruit and vegetables contain a wide variety of antioxidant phenolics and that the American average consumption of fruit and vegetables contributes a large amount of antioxidants in the diet. Dietary modification through the balanced consumption of fruit and vegetables, therefore, is likely to be more important and effective than nutritional supplements for the primary prevention of chronic diseases.

REFERENCES

1 Doll R, An overview of the epidemiological evidence linking diet and cancer. *Proc Nutr Soc* **49**:119–131 (1990).

2 Bravo L, Polyphenols: chemistry, dietary sources, metabolism, and nutritional significance. *Nutr Rev* **56**:317–333 (1998).

3 Hertog MGL, Sweetnam PM, Fehily AM, Elwood PC and Kromhout D, *Potentially Anticarcinogenic Secondary Metabolites from Fruit and Vegetables*. Clarendon Press, Oxford (1997).

4 Hertog MGL, Feskens EJM, Hollman PCH, Katan MB and Kromhout D, Dietary antioxidant flavonoids and risk of coronary heart disease: the Zutphen elderly study. *Lancet* **342**:1007–1011 (1993).

5 Hertog MGL, Kromhout D, Aravanis C, Blackburn H, Buzina R, Fidanza F, Giampaoli S, Jansen A, Menotti A, Nedeljkovic S, Pekkarinen M, Simic BS, Toshima H, Feskens EJM, Hollman PCH and Katan MB, Flavonoid intake and long-term risk of coronary heart disease and cancer in the seven countries study. *Arch Intern Med* **155**:381–386 (1995).

6 Hertog MGL, Sweetnam PM, Fehily AM, Elwood PC and Kromhout D, Antioxidant flavonols and ischaemic heart disease in a Welsh population of men. The Caerphilly study. *Am J Clin Nutr* **65**:1489–1494 (1997).

7 Ames BN, Shigenaga MK and Hagen TM, Oxidants, antioxidants, and the degenerative diseases of aging. *Proc Natl Acad Sci USA* **90**:7915–7922 (1993).

8 Wang H, Cao G and Prior RL, Total antioxidant capacity of fruits. *J Agric Food Chem* **44**:701–705 (1996).

9 Middleton E Jr and Kandaswami C, *The Flavonoids: Advances in Research since 1986*, Ed by Harborne JB. Chapman & Hall, London, pp 619–652 (1994).

10 Muldoon MF and Kritchevsky SB, Flavonoids and heart disease. *Br Med J* **312**:458–459 (1996).

11 Agullo G, Gamet-Payrastre L, Manenti S, Viala C, Rémésy C, Chap H and Payrastre B, Relationship between flavonoid structure and inhibition of phosphatidylinositol 3-kinase: a comparison with tyrosine kinase and protein kinase C inhibition. *Biochem Pharmac* **53**:1649–1657 (1997).

12 Meyer AS, Yi O-S, Pearson DA, Waterhouse AL and Frankel EN, Inhibition of human low-density lipoprotein oxidation in relation to composition of phenolic antioxidants in grapes (*Vitis vinifera*). *J Agric Food Chem* **45**:1638–1643 (1997).

13 Ryu BH, Antioxidative activity of flavonoid on oxidation of human low density lipoprotein induced by macrophages and copper. *Food Sci Biotechnol* **11**:84–88 (2002).

14 Willett WC, Diet, nutrition, and avoidable cancer. *Environ Health Perspect* **103**:165–170 (1995).

15 Doll R and Peto R, Avoidable risks of cancer in the United States. *J Natl Cancer Inst* **66**:1197–1265 (1981).

16 Block G, The data support a role for antioxidants in reducing cancer risk. *Nutr Rev* **50**:207–213 (1992).

17 Block G, Patterson B and Subar A, Fruits, vegetables and cancer prevention: a review of the epidemiological evidence. *Nutr Cancer* **18**:1–29 (1992).

18 Rimm EB, Katan MB, Ascherio A, Stampfer MJ and Willett WC, Relation between intake of flavonoids and risk of coronary heart disease in male health professionals. *Ann Intern Med* **125**:384–389 (1996).

19 Kuhnau J, The flavonoids, a class of semi-essential food components: their role in human nutrition. *Wld Rev Nutr Diet* **24**:117–191 (1976).

20 Hertog MGL, Hollman PCH, Katan MB and Kromhout D, Intake of potentially anticarcinogenic flavonoids and their determinants in adults in the Netherlands. *Nutr Cancer* **20**:21–29 (1993).

21 Vinson JA, Hao Y, Su X and Zubik L, Phenolic antioxidant quantity and quality in foods: vegetables. *J Agric Food Chem* **46**:3630–3634 (1998).

22 Vinson JA, Su X, Zubik L and Bose P, Phenol antioxidant quantity and quality in foods: fruits. *J Agric Food Chem* **49**:5315–5321 (2001).

23 Kim D-O, Lee KW, Lee HJ and Lee CY, Vitamin C equivalent antioxidant capacity (VCEAC) of phenolic phytochemicals. *J Agric Food Chem* **50**:3713–3717 (2002).

24 Gil MI, Tomás-Barberán FA, Hess-Pierce B and Kader AA, Antioxidant capacities, phenolic compounds, carotenoids, and vitamin C contents of nectarine, peach, and plum cultivars from California. *J Agric Food Chem* **50**:4976–4982 (2002).

25 Leong LP and Shui G, An investigation of antioxidant capacity of fruits in Singapore markets. *Food Chem* **76**:69–75 (2002).

26 Economic Research Service, US Department of Agriculture (2003). http://www.ers.usda.gov/data/foodconsumption/ [accessed 20 March 2004].

27 National Nutrient Database, US Department of Agriculture (2003). http://www.nal.usda.gov/fnic/foodcomp/Data/SR17/sr17.html [accessed 20 March 2004].

28 Kim D-O and Lee CY, *Current Protocols in Food Analytical Chemistry*, Ed by Wrolstad ERE. J Wiley, New York, Unit I1.2.1–2.12 (2002).
29 Kim D-O, Jeong SW and Lee CY, Antioxidant capacity of phenolic phytochemicals from various cultivars of plums. *Food Chem* **81**:321–326 (2003).
30 Zhishen J, Mengcheng T and Jianming W, The determination of flavonoid contents in mulberry and their scavenging effects on superoxide radicals. *Food Chem* **64**:555–559 (1999).
31 Chun OK, Kim D-O and Lee CY, Superoxide radical scavenging activity of the major polyphenols in fresh plums. *J Agric Food Chem* **51**:8067–8072 (2003).
32 Chun OK, Kim D-O, Moon HY, Kang HG, Kim MH and Lee CY, Contribution of individual polyphenolics to total antioxidant capacity of plums. *J Agric Food Chem* **51**:7240–7245 (2003).
33 Proteggente AR, Pannala AS, Paganga G, van Buren L, Wagner E, Wiseman S, van de Put F, Dacombe C and Rice-Evans CA, The antioxidant activity of regularly consumed fruit and vegetables reflects their phenolic and vitamin C composition. *Free Radic Res* **36**:217–233 (2002).
34 Ju ZY and Howard LR, Effects of solvent and temperature on pressurized liquid extraction of anthocyanins and total phenolics from dried red grape skin. *J Agric Food Chem* **51**:5207–5213 (2003).
35 Lee CY and Smith NL, Apples: an important source of antioxidants in the American diet. *NY Fruit Q* **8**:15–17 (2000).
36 Sun J, Chu Y-F, Wu X and Liu RH, Antioxidant and antiproliferative activities of common fruits. *J Agric Food Chem* **50**:7449–7454 (2002).
37 Murcia MA, Jiménez AM and Martínez-Tomé M, Evaluation of the antioxidant properties of Mediterranean and tropical fruits compared with common food additives. *J Food Prot* **64**:2037–2046 (2001).
38 Velioglu YS, Mazza G, Gao L and Oomah BD, Antioxidant activity and total phenolics in selected fruits, vegetables, and grain products. *J Agric Food Chem* **46**:4113–4117 (1998).
39 Halvorsen B, Holte K, Myhrstad M, Barikmo I, Hvattum E, Remberg S, Wold A, Haffner K, Baugerod H, Andersen L, Moskaug J, Jacobs DJ and Blomhoff R, A systematic screening of total antioxidants in dietary plants. *J Nutr* **132**:461–471 (2002).
40 Wang H, Cao G and Prior RL, Total antioxidant capacity of fruits. *J Agric Food Chem* **44**:701–705 (1996).
41 Estrada B, Bernal MA, Federico JD, Pomar F and Merino F, Fruit development in *Capsicum annuum*: changes in capsaicin, lignin, free phenolics, and peroxidase patterns. *J Agric Food Chem* **48**:6234–6239 (2000).
42 Lee Y, Howard LR and Villalon B, Flavonoids and antioxidant activity of fresh pepper (*Capsicum annuum*) cultivars. *J Food Sci* **60**:473–476 (1995).
43 Cao G, Sofic E and Prior RL, Antioxidant capacity of tea and common vegetables. *J Agric Food Chem* **44**:3426–3431 (1996).
44 Yin M-C, Hwang S-W and Chan K-C, Nonenzymatic antioxidant activity of four organosulfur compounds derived from garlic. *J Agric Food Chem* **50**:6143–6147 (2002).
45 Kris-Etherton PM, Hecker KD, Bonanome A, Coval SM, Binkoski AE, Hilpert KF, Griel AE and Etherton TD, Bioactive compounds in foods: their role in the prevention of cardiovascular disease and cancer. *Am J Med* **113**:71S–88S (2002).
46 Furuta S, Nishiba Y and Suda I, Fluorometric assay for screening antioxidative activity of vegetables. *J Food Sci* **62**:526–528 (1997).
47 Tsushida T, Suzuki M and Kurogi M, Evaluation of antioxidant activity of vegetable extracts and determination of some active compounds. *Nippon Shokuhin Kogyo Gakkaishi* **41**:611–618 (1994).
48 Lee K, Kim Y, Lee H and Lee C, Cocoa has more phenolic phytochemicals and a higher antioxidant capacity than teas and red wine. *J Agric Food Chem* **51**:7292–7295 (2003).
49 Chen C-W and Ho C-T, Antioxidant properties of polyphenols extracted from green and black teas. *J Food Lipids* **2**:35–46 (1995).
50 Cao G, Sofic E and Prior RL, Antioxidant and prooxidant behavior of flavonoids: structure-activity relationships. *Free Radic Biol Med* **22**:749–760 (1997).
51 Eberhardt MV, Lee CY and Liu RH, Antioxidant activity of fresh apples. *Nature* **405**:903–904 (2000).
52 Hyson D (ed), *The Health Benefits of Fruits and Vegetables: a Scientific Overview for Health Professionals*. US Food and Drug Administration and Produce Marketing Association (2002).
53 Liu RH, Protective role of phytochemicals in whole foods: implications for chronic disease prevention. *Appl Biotechnol Food Sci Policy* **1**:39–46 (2003).