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ORIGINAL ARTICLE

Identification of the 100 richest dietary sources of polyphenols: an application of the Phenol-Explorer database

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Background/Objectives: The diversity of the chemical structures of dietary polyphenols makes it difficult to estimate their total content in foods, and also to understand the role of polyphenols in health and the prevention of diseases. Global redox colorimetric assays have commonly been used to estimate the total polyphenol content in foods. However, these assays lack specificity. Contents of individual polyphenols have been determined by chromatography. These data, scattered in several hundred publications, have been compiled in the Phenol-Explorer database. The aim of this paper is to identify the 100 richest dietary sources of polyphenols using this database.

Subjects/Methods: Advanced queries in the Phenol-Explorer database (www.phenol-explorer.eu) allowed retrieval of information on the content of 502 polyphenol glycosides, esters and aglycones in 452 foods. Total polyphenol content was calculated as the sum of the contents of all individual polyphenols. These content values were compared with the content of antioxidants estimated using the Folin assay method in the same foods. These values were also extracted from the same database. Amounts per serving were calculated using common serving sizes.

Results: A list of the 100 richest dietary sources of polyphenols was produced, with contents varying from 15 000 mg per 100 g in cloves to 10 mg per 100 ml in rosé wine. The richest sources were various spices and dried herbs, cocoa products, some darkly coloured berries, some seeds (flaxseed) and nuts (chestnut, hazelnut) and some vegetables, including olive and globe artichoke heads. A list of the 89 foods and beverages providing more than 1 mg of total polyphenols per serving was established. A comparison of total polyphenol contents with antioxidant contents, as determined by the Folin assay, also showed that Folin values systematically exceed the total polyphenol content values.

Conclusions: The comprehensive Phenol-Explorer data were used for the first time to identify the richest dietary sources of polyphenols and the foods contributing most significantly to polyphenol intake as inferred from their content per serving.

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Introduction

Polyphenols are common antioxidants present in a large number of foods and beverages of plant origin. A mean intake of about 1 g per day has been reported (Kühnau, 1976; Ovaskainen *et al.*, 2008). All polyphenols are characterised by the presence in their structure of one or several phenolic groups, capable of reducing reactive oxygen species and various organic substrates and minerals. These redox properties explain the considerable interest in their role in the prevention of several major chronic diseases associated with oxidative stress, such as cardiovascular diseases, cancers, type II diabetes, neurodegenerative diseases or osteoporosis (Scalbert *et al.*, 2005).

Polyphenols show highly diverse structures and over 500 different molecules are known in foods (Neveu *et al.*, 2010; Pérez-Jiménez *et al.*, 2010). This diversity must be taken into account when considering bioavailability, biological

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properties and health effects, as the latter largely depend on their specific chemical structures (Manach *et al*., 2005; Loke *et al*., 2008). The diversity of polyphenols also makes it difficult to estimate the total polyphenol content of foods, an important fact for food and nutrition researchers and the food industry.

Ranks of foods and beverages that are richest in polyphenols have been published. For these estimations, relatively easily performed colorimetric redox assays, based on the generic reducing property of phenolic groups, have been used (Vinson *et al*., 1998, 1999, 2001, 2003). One of the most commonly used tests is the Folin assay (Singleton and Rossi, 1965; Scalbert, 1992). However, such global assays are prone to interference from non-phenolic food constituents. This interference may be limited by a preliminary solid phase extraction of polyphenols, but this approach is yet to be applied to a large variety of foods (Brat *et al*., 2006).

The United States Department of Agriculture (USDA) database, one of the most complete sources of information on the content of individual polyphenols in foods, provides composition data for 38 flavonoid aglycones in over 300 foods (USDA, 2004, 2007, 2008). This database has been used to build food composition tables for flavonoids and to estimate their intake in several cohorts (Mink *et al*., 2007; Ovaskainen *et al*., 2008). More recently, we have developed the more comprehensive Phenol-Explorer database, which includes mean content values for 502 polyphenols in 452 foods (Neveu *et al*., 2010; Pérez-Jiménez *et al*., 2010). This database not only contains data on flavonoids but also composition
data for phenolic acids, lignans and stilbenes. The aim of the present work was to exploit the Phenol-Explorer data to establish a list of the 100 richest dietary sources of polyphenols and to determine the amount of polyphenols present in a food serving using common serving sizes. Polyphenol contents and amounts per serving are also compared with the amount of antioxidants in the same foods, as determined by the Folin colorimetric assay.

Materials and methods

Data on the polyphenol content in foods were extracted from the Phenol-Explorer database (www.phenol-explorer.eu). The database has been fully described elsewhere (Neveu *et al*., 2010; Pérez-Jiménez *et al*., 2010). Advanced queries in the Phenol-Explorer database allowed retrieval of information on polyphenol content, as determined by different types of analytical methods: chromatography (most often reverse-phase high-performance liquid chromatography (HPLC) and gas chromatography), normal-phase HPLC for proanthocyanidins and the Folin assay for total antioxidants. The total polyphenol content was calculated as the sum of the contents of all individual polyphenols as determined by chromatography. This includes the content of proanthocyanidin dimers and trimers. When content values for proanthocyanidins, as determined by normal-phase chromatography (dimers to polymers), were available, they were added, instead of the values obtained by reverse-phase HPLC for dimers and trimers. The main polyphenol standards used for determining Folin values in Phenol-Explorer included gallic acid, catechin and caffeic acid (59, 14 and 11%, respectively, of the values collated in the database). These three standards show similar response factors when calculated on a weight basis (Scalbert, 1992), and data are therefore roughly comparable, even if different standards were used. However, Folin values should be considered as a rough estimate of the antioxidant content because of possible differences in the response of the various antioxidants present in a food extract.

For foods containing significant amounts of polyphenols that are attached to the food matrix and can only be solubilised and quantified after basic or acid hydrolysis (phenolic acids in cereals and lignans in flaxseed) (Pérez-Jiménez *et al*., 2010), content values obtained by chromatography after hydrolysis were used instead of those for free polyphenols, as directly determined by chromatography. Total content of polyphenol aglycones was calculated by converting the content of each individual polyphenol in foods to that of the corresponding aglycone, taking into account the molecular weights of the glycosides or esters and aglycones. Amounts of polyphenols contained in a food serving were calculated on the basis of serving sizes published by the Food Standards Agency, UK (Food Standards Agency, 2002), the USDA (Wu *et al*., 2004) and by Cassidy *et al*. (2000) for some soy products. Some extrapolations were made for missing data; for example, in the case of a non-documented fruit juice, the serving size of a juice prepared from a related fruit was used. A retention factor was applied for cooked foods when polyphenol contents were only available for raw foods (for example, beans or pasta), to take into account the change in weight during cooking (Bognar, 2002).

Results

Foods richest in polyphenols
The content values of all known individual polyphenols collected in the Phenol-Explorer database from the scientific literature were used to calculate total polyphenol contents of 452 foods. Data for the 100 foods with the highest polyphenol contents are shown in Table 1.

The food group with the highest number of items in this list is the seasoning group (22 items), followed by fruits (20 items), seeds (16 items), vegetables (16 items), non-alcoholic beverages (11 items), cereals (10 items), cocoa products (4 items), alcoholic beverages (3 items) and oils (2 items). Total polyphenol contents ranged from more than 15 000 mg per 100 g in cloves to 7.8 mg per 100 ml in rosé wine.

Table 1 Polyphenol and antioxidant content in the 100 richest foods (mg per 100 g or mg per 100 ml)

Food	*Food group*	*Polyphenols*[a]		*Polyphenols AE*[a]		*Antioxidants*[b]	
		Content	*Rank*	*Content*	*Rank*	*Content*	*Rank*
Cloves	Seasonings	15 188	1	15 188	1	16 047	1
Peppermint, dried	Seasonings	11 960	2	7920	2	980	26
Star anise	Seasonings	5460	3	5460	3	1810	16
Cocoa powder	Cocoa products	3448	4	3294	4	1104	24
Mexican oregano, dried	Seasonings	2319	5	2137	5	—	—
Celery seed	Seasonings	2094	6	1007	10	—	—
Black chokeberry	Fruits	1756	7	1432	7	1752	17
Dark chocolate	Cocoa products	1664	8	1618	6	1860	13
Flaxseed meal	Seeds	1528[c]	9	1220[c]	8	—	—
Black elderberry	Fruits	1359	10	804	13	1950	12
Chestnut	Seeds	1215	11	1215	9	2757	9
Common sage, dried	Seasonings	1207	12	893	12	2920	8
Rosemary, dried	Seasonings	1018	13	522	14	2519	10
Spearmint, dried	Seasonings	956	14	491	18	6575	3
Common thyme, dried	Seasonings	878	15	464	19	1815	15
Lowbush blueberry	Fruits	836	16	496	15	471	35
Blackcurrant	Fruits	758	17	464	20	821	29
Capers	Seasonings	654	18	389	21	3600	6
Black olive	Vegetables	569	19	320	22	117	53
Highbush blueberry	Fruits	560	20	295	23	205	40
Hazelnut	Seeds	495	21	493	16	687	30
Pecan nut	Seeds	493	22	493	17	1816	14
Soy flour	Seeds	466	23	267	27	—	—
Plum	Fruits	377	24	285	24	411	35
Green olive	Vegetables	346	25	233	28	161	47
Sweet basil, dried	Seasonings	322	26	166	34	4317	4
Curry, powder	Seasonings	285	27	285	25	1075	25
Sweet cherry	Fruits	274	28	145	38	144	48
Globe artichoke heads	Vegetables	260	29	154	35	1142	23
Blackberry	Fruits	260	30	180	33	570	31
Roasted soybean	Seeds	246	31	153	36	—	—
Milk chocolate	Cocoa products	236	32	236	27	854	28
Strawberry	Fruits	235	33	205	29	268	36
Red chicory	Vegetables	235	34	131	41	129	51
Red raspberry	Fruits	215	35	107	46	980	27
Coffee, filter	Non-alcoholic beverages	214	36	110	45	267	37
Ginger, dried	Seasonings	202	37	202	30	473	32
Whole grain hard wheat flour	Cereals	201[c]	38	201[c]	21	186	46
Prune	Fruits	194	39	100	49	1195	21
Almond	Seeds	187	40	185	32	191	45
Black grape	Fruits	169	41	124	42	205	41
Red onion	Vegetables	168	42	99	50	91	60
Green chicory	Vegetables	166	43	117	44	—	—
Common thyme, fresh	Seasonings	163	44	118	43	1173	23
Refined maize flour	Cereals	153[c]	45	153[c]	37	102	59
Soy, tempeh	Seeds	148	46	101	48	—	—
Whole grain rye flour	Cereals	143[c]	47	143[c]	39	72	66
Apple	Fruits	136	48	136	40	205	42
Spinach	Vegetables	119	49	68	55	248	38
Shallot	Vegetables	113	50	67	56	115	54
Lemon verbena, dried	Seasonings	106	51	106	47	—	—
Black tea	Non-alcoholic beverages	102	52	90	52	104	58
Red wine	Alcoholic beverages	101	53	91	51	215	39
Green tea	Non-alcoholic beverages	89	54	82	53	62	67
Soy yogurt	Seeds	84	55	51	60	—	—
Yellow onion	Vegetables	74	56	49	61	75	64
Soy meat	Seeds	73	57	47	63	—	—
Whole grain wheat flour	Cereals	71[c]	58	71[c]	54	90	61
Pure apple juice	Non-alcoholic beverages	68	59	61	57	34	75
Pure pomegranate juice	Non-alcoholic beverages	66	60	37	64	204	43
Extra-virgin olive oil	Oils	62	61	33	67	55	70
Black bean	Seeds	59	62	36	66	1390	20
Peach	Fruits	59	63	54	59	107	57

Table 1 *Continued*

Food	*Food group*	*Polyphenols*[a]		*Polyphenols AE*[a]		*Antioxidants*[b]	
		Content	*Rank*	*Content*	*Rank*	*Content*	*Rank*
Pure blood orange juice	Non-alcoholic beverages	56	64	28	71	72	67
Cumin	Seasonings	55	65	55	58	2038	11
Pure grapefruit juice	Non-alcoholic beverages	53	66	23	76	54	72
White bean	Seeds	51	67	31	69	138	49
Chinese cinnamon	Seasonings	48	68	48	62	—	—
Pure blond orange juice	Non-alcoholic beverages	46	69	20	81	—	—
Broccoli	Vegetables	45	70	21	79	198	44
Redcurrant	Fruits	43	71	23	77	448	36
Soy tofu	Seeds	42	72	25	74	—	—
Pure lemon juice	Non-alcoholic beverages	42	73	20	82	—	—
Whole grain oat flour	Cereals	37[c]	74	37[c]	65	82	65
Apricot	Fruits	34	75	15	85	133	53
Caraway	Seasonings	33	76	33	68	2913	7
Refined rye flour	Cereals	31[c]	77	31[c]	70	45	74
Asparagus	Vegetables	29	78	11	90	75	65
Walnut	Seeds	28	79	28	71	1576	19
Potato	Vegetables	28	80	15	86	54	73
Ceylan cinnamon	Seasonings	27	81	27	73	9070	2
Parsley, dried	Seasonings	25	82	25	75	1584	18
Nectarine	Fruits	25	83	20	83	55	71
Curly endive	Vegetables	24	84	15	87	—	—
Marjoram, dried	Seasonings	23	85	22	78	3,846	5
Red lettuce	Vegetables	23	86	14	88	114	58
Chocolate beverage with milk	Non-alcoholic beverages	21	87	21	80	—	—
Quince	Fruits	19	88	12	89	—	—
Endive (Escarole)	Vegetables	18	89	11	91	—	—
Soy milk	Non-alcoholic beverages	18	90	11	92	—	—
Pure pummelo juice	Non-alcoholic beverages	18	91	7.9	97	—	—
Rapeseed oil	Oils	17	92	17	84	18	78
Pear	Fruits	17	93	11	93	108	59
Soybean sprout	Seeds	15	94	10	95	—	—
Green grape	Fruits	15	95	7.6	98	122	55
Carrot	Vegetables	14	96	6.6	100	58	71
Vinegar	Seasonings	13	97	11	94	—	—
Soy cheese	Seeds	12	98	7.6	99	—	—
White wine	Alcoholic beverages	10	99	8.6	96	32	77
Rosé wine	Alcoholic beverages	10	100	7.8	98	82	63

Abbreviation: AE, (polyphenols as) aglycone equivalents.
[a]Sum of the content of individual polyphenols as determined by chromatography and of proanthocyanidin oligomers as determined by direct-phase high-performance liquid chromatography.
[b]Determined by the Folin assay. Some foods with a high antioxidant content as determined by the Folin assay are not included in the table due the absence of documented data on their polyphenol content as obtained by chromatography. Their antioxidant contents are as follows: lentils (6553 mg/100 g), dried oregano (5452 mg/100 g), dried summer savory (4512 mg/100 g), dried sweet bay (4170 mg/100 g), dried camomile (2483 mg/100 g), dried coriander (2260 mg/100 g), fenugreek (2250 mg/100 g), dried winter savory (1880 mg/100 g), pistachio (1490 mg/100 g), hyssop (1623 mg/100 g), red swiss chard leaves (1320 mg/100 g), dried dill (1250 mg/100 g), raisin (1065 mg/100 g), broad bean seeds (1039 mg/100 g), black pepper spice (1000 mg/100 g), fresh peppermint (980 mg/100 g), black raspberry (980 mg/100 g), fig (960 mg/100 g), fresh oregano (953 mg/100 g), fresh lemon balm (900 mg/100 g), fenugreek seed (830 mg/100 g), white swiss chard leaves (830 mg/100 g), white pepper spice (780 mg/100 g), fresh tarragon (570 mg/100 g), peanut butter (536 mg/100 g), bilberry (525 mg/100 g), dried date (488 mg/100 g), green pepper spice (380 mg/100 g).
[c]Polyphenol content determined by chromatography after hydrolysis of the glycosides and esters.

Foods richest in antioxidants

The Folin assay provides a crude estimate of the content of total antioxidants. This test is also commonly used to estimate the total polyphenol content in foods, as polyphenols with different structures have a similar response factor (Singleton and Rossi, 1965; Scalbert, 1992). However, this test is not specific for polyphenols, as the Folin reagent also reacts with other food constituents such as ascorbic acid. This assay should therefore be regarded as a global antioxidant assay, comparable to other redox assays such as the Oxygen Radical Absorbance Capacity assay. The antioxidant contents determined by the Folin assay in the same 100 foods rich in polyphenols are given in Table 1. These values are compared with the total contents of polyphenols expressed as aglycone equivalents because it is the aglycone with its phenolic group(s) that reacts with the Folin oxidant. Antioxidant contents were systematically higher than the total polyphenol contents (Figure 1).

Table 2 Food servings providing at least 1 mg polyphenols with their polyphenol and antioxidant contents (mg per serving)

Food	Food group	Serving[a] (g)	Polyphenols[b]		Polyphenols AE[b]		Antioxidants[c]	
			Content	Rank	Content	Rank	Content	Rank
Black elderberry	Fruits	145[d]	1956	1	1196	2	2808	1
Black chokeberry	Fruits	145[d]	1595	2	1114	1	2523	2
Blackcurrant	Fruits	145[d]	1092	3	689	4	1182	5
Highbush blueberry	Fruits	145[d]	806	4	425	5	321	14
Globe artichoke heads	Vegetables	168	436	5	259	8	1918	3
Coffee, filter	Non-alcoholic beverages	190	408	6	209	13	507	11
Lowbush blueberry	Fruits	145[d]	395	7	714	3	678	8
Sweet cherry	Fruits	145[d]	394	8	209	14	249	20
Strawberry	Fruits	166[d]	390	9	340	6	480	12
Blackberry	Fruits	144[d]	374	10	260	9	821	6
Plum	Fruits	85	320	11	242	11	349	13
Red raspberry	Fruits	144	310	12	154	17	213	22
Flaxseed meal	Seeds	20[e]	306[f]	13	244[f]	10	—	—
Dark chocolate	Cocoa products	17	283	14	275	7	316	15
Chestnut	Seeds	19	230	15	231	12	524	10
Black tea	Non-alcoholic beverages	195	197	16	175	15	204	23
Green tea	Non-alcoholic beverages	195	173	17	164	16	121	31
Pure apple juice	Non-alcoholic beverages	248	168	18	151	18	84	38
Apple	Fruits	110	149	19	147	19	221	21
Whole grain rye bread	Cereals	120	146[f]	20	146[f]	20	—	—
Hazelnut	Seeds	28[e]	138	21	138	21	192	24
Red wine	Alcoholic beverages	125	126	22	117	23	269	19
Soy yogurt	Seeds	125	105	23	53	28	—	—
Cocoa powder	Cocoa products	3	103	24	99	25	33	46
Pure pomegranate juice	Non-alcoholic beverages	150	99	25	50	31	306	16
Soy flour	Seeds	20[e]	93	26	53	29	—	—
Black grape	Fruits	54	91	27	113	24	92	36
Black olive	Vegetables	15	85	28	48	32	17	56
Pure grapefruit juice	Non-alcoholic beverages	150	79	29	39	37	82	39
Pure blood orange juice	Non-alcoholic beverages	154	71	30	31	42	111	33
Milk chocolate	Cocoa products	32	75	31	75	26	273	17
Spinach	Vegetables	59	70	32	40	34	170	26
Pecan nut	Seeds	15	69	33	69	27	272	18
Prune	Fruits	32	62	34	32	40	—	—
Redcurrant	Fruits	144	62	35	119	22	646	9
Soy, tempeh	Seeds	40	59	36	40	35	—	—
Peach	Fruits	99[e]	59	37	52	30	105	34
Soy tofu	Seeds	130	54	38	32	41	—	—
Green olive	Vegetables	15	52	39	35	39	24	51
Black bean	Seeds	35	52	40	14	56	1216	4
Red onion	Vegetables	30	50	41	30	43	31	47
Green grape	Fruits	54	48	42	46	33	66	41
White bean	Seeds	35	44	43	11	60	121	32
Chocolate beverage with milk	Non-alcoholic beverages	187	39	44	39	38	—	—
Roasted soybean	Seeds	15	37	45	40	36	—	—
Potato	Vegetables	128	36	46	23	45	69	40
Shallot	Vegetables	32	36	47	21	47	—	—
Soy milk	Non-alcoholic beverages	187	34	48	20	48	—	—
Red chicory	Vegetables	14	33	49	18	49	18	54
Broccoli	Vegetables	72	33	50	15	53	142	30
Soy meat	Seeds	40[e]	29	51	19	50	—	—
Whole grain rye flour	Cereals	20	29[f]	52	29[f]	44	14	59
Pure pummelo juice	Non-alcoholic beverages	154	27	53	12	58	—	—
Nectarine	Fruits	99	25	54	20	48	44	44
Green chicory	Vegetables	14	23	55	16	49	—	—
Pear	Fruits	138	23	56	15	54	149	29
Beer	Alcoholic beverages	574	22	57	22	46	160	27
Yellow onion	Vegetables	30	22	58	15	55	23	52
Apricot	Fruits	65	22	59	10	61	86	37
Asparagus	Vegetables	75	22	60	8.6	64	56	42
Quince	Fruits	100	19	61	12	59	—	—
Almond	Seeds	10	19	62	0.8	88	6.2	64
Whole grain wheat flour	Cereals	20	14[f]	63	14[f]	57	18	55
White wine	Alcoholic beverages	125	13	64	10	62	40	45

Table 2 *Continued*

Food	*Food group*	*Serving[a] (g)*	*Polyphenols[b]*		*Polyphenols AE[b]*		*Antioxidants[c]*	
			Content	*Rank*	*Content*	*Rank*	*Content*	*Rank*
Rosé wine	Alcoholic beverages	125	12	65	10	63	10	62
Dark beer	Alcoholic beverages	574	10	66	5.2	67	102	35
Extra virgin olive oil	Oils	16	10	67	4.8	68	8.8	63
Soybean sprout	Seeds	60	9.3	68	6.0	66	—	—
Carrot	Vegetables	54	7.6	69	3.5	69	31	48
Bilberry	Fruits	145[d]	7.4	70	7.4	65	756	7
Pure lemon juice	Non-alcoholic beverages	15	6.3	71	1.8	80	—	—
Red lettuce	Vegetables	24	5.4	72	3.4	70	27	50
Soy cheese	Seeds	40[e]	4.9	73	3.1	72	—	—
Green bean	Vegetables	60	4.8	74	3.4	71	185	25
Curly endive	Vegetables	14	3.4	75	2.0	78	—	—
Cauliflower	Vegetables	38	2.7	76	2.7	73	31	49
Peanut roasted dehulled	Seeds	40	2.6	77	2.6	74	17	57
Rapeseed oil	Oils	16	2.5	78	2.5	75	—	—
Pumpkin	Vegetables	60	2.5	79	2.0	79	52	43
Pasta	Cereals	60	2.5	80	2.5	76	—	—
Banana	Fruits	97	2.5	81	2.5	77	150	28
Endive (escarole)	Vegetables	14	2.5	82	1.5	82	—	—
Tomato	Vegetables	50	2.1	83	1.2	83	22	53
Green lettuce	Vegetables	24	1.9	84	1.1	85	16	58
White onion	Vegetables	30	1.6	85	1.0	87	13	61
Refined oat flour	Cereals	20	1.6[f]	86	1.6[f]	81	—	—
Refined wheat flour	Cereals	20	1.2[f]	87	1.2[f]	84	14	60
Pomegranate	Fruits	100	1.1	88	1.1	86	—	—
Sweet green pepper	Vegetables	20	0.9	89	0.5	89	0.4	65

Abbreviation: AE, (polyphenols as) aglycone equivalents.
[a]From the Food Standards Agency, UK (Food Standards Agency, 2002), except for values marked with a superscript.
[b]Sum of individual polyphenols determined by reverse-phase high-performance liquid chromatography (HPLC) and proanthocyanidins oligomers determined by direct-phase HPLC.
[c]Determined by the Folin assay.
[d]From Wu *et al.* (2004).
[e]From Cassidy *et al.* (2000).
[f]Polyphenol content determined by chromatography after hydrolysis of the glycosides and esters.

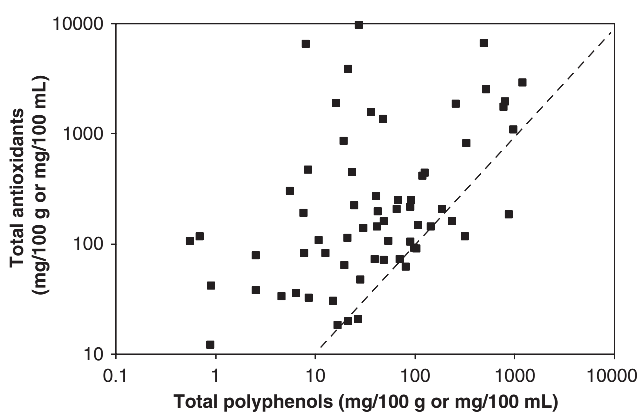

Figure 1 Comparison of polyphenol and antioxidant contents in various foods measured by chromatography and the Folin assay, respectively. Polyphenol contents are the sum of the contents of individual polyphenols expressed as aglycone equivalents.

Foods richest in polyphenols per serving

The amounts of polyphenols contained in a food serving were calculated for all foods documented in the Phenol-Explorer database. Foods containing more than 1 mg per serving are presented in Table 2. This list includes 89 foods and beverages: 23 fruits, 23 vegetables, 16 seeds, 10 non-alcoholic beverages, 6 cereals, 5 alcoholic beverages, 4 cocoa products and 2 oils. Three berries contain more than 1000 mg of polyphenols per serving. A total of 21 foods or beverages provide 100–1000 mg polyphenols per serving, 41 foods contain 10–100 mg and 24 foods 1–10 mg. Some foods rich in polyphenols, such as herbs and spices (Table 1), are absent from Table 2, as no data on serving sizes were found.

When results were expressed as aglycone equivalents (Table 2), the amount of polyphenols contained in a serving was higher than 1000 mg for 2 foods (black elderberry and black chokeberry), between 100 and 1000 mg for 22 foods, between 10 and 100 mg for 40 foods and lower than 1 mg for 25 foods.

The amount of antioxidants as determined by the Folin assay in a serving of the same foods is also shown in Table 2. Five foods contain more than 1000 mg antioxidants per serving (black elderberry, black chokeberry, globe artichoke heads, black bean and blackcurrant), 30 foods between 100 and 1000 mg and 27 foods between 10 and 100 mg.

Discussion

A clear identification of the richest dietary sources of polyphenols is necessary to better understand and exploit the health-promoting effects of polyphenols, a matter of interest for the food industry, food scientists and nutritionists. However, the wide variety of chemical structures among polyphenols makes it difficult to estimate their content in foods, as different methods of analysis must be used to cover the whole range of molecules known to exist in foods. For this reason, global colorimetric assays such as the Folin assay have been used to determine the total polyphenol content in foods (Vinson *et al.*, 1998; Vinson *et al.*, 2001). Folin values should be considered as an estimate of antioxidant content rather than the total polyphenol content, unless applied to a purified polyphenol fraction (Brat *et al.*, 2006). Folin values are generally well correlated to the content of antioxidants as measured by other redox assays, such as the Oxygen Radical Absorbance Capacity assay (Velioglu *et al.*, 1998). As seen in Figure 1, the Folin values are most often higher than the total content of polyphenols, because of the presence and influence of non-phenolic antioxidants on the assay.

The most reliable method to estimate total polyphenol content is the analysis of all individual phenolic compounds. However, because of the diversity of compounds and methods needed for their analysis, the comparison of total polyphenol content in a variety of foods can only be based on the compilation of literature data. The most complete source of food composition data for polyphenols has been the USDA database for 38 flavonoid aglycones (USDA, 2004, 2007, 2008). These data have been used and subsequently augmented with other literature sources for phenolic acids to determine the total polyphenol contents in foods and to calculate polyphenol intake in cohorts (Mink *et al.*, 2007; Ovaskainen *et al.*, 2008). The recently developed Phenol-Explorer database provides composition data for 502 polyphenols (glycosides, esters and aglycones of flavonoids, phenolic acids, lignans, stilbenes and other polyphenols) in 452 foods. It is today the most complete database on the content of polyphenols in foods (Neveu *et al.*, 2010). These data are used here for the first time to calculate the total polyphenol contents in these various foods and to identify the 100 richest sources of dietary polyphenols. All details on the composition of each food considered here can be obtained on the Phenol-Explorer website (www.phenol-explorer.eu; Neveu *et al.*, 2010).

The richest sources of polyphenols are spices and herbs (Table 1). Spices such as cloves or star anise contain high amounts of phenolic flavours such as eugenol (cloves) or anethole (star anise). Dried herbs contain high amounts of flavanones such as eriocitrin (peppermint) or pinocembrin (Mexican oregano) and/or high amounts of hydroxycinnamic acids such as rosmarinic acid in herbs from the Lamiaceae family (peppermint, sage, rosemary, spearmint, thyme).

Cocoa powder and chocolate are also rich in polyphenols, mainly catechins and proanthocyanidins. A number of berries also appear at the top of the list with high contents of anthocyanins. As expected, the berries richest in polyphenols are all darkly coloured: black chokeberry, black elderberry, blueberry and blackcurrant (Table 1). Three other intensely coloured fruits follow down the list: plum, cherry and blackberry. Less-coloured fruits are found further down: strawberry, raspberry and grape, followed by pome and drupe fruits (apple, peach, apricot, nectarine, pear).

Several seeds and nuts are also found among the richest sources of polyphenols: flaxseed rich in lignan secoisolariciresinol, chestnut and walnut rich in ellagitannins, hazelnut, pecan nut and almond rich in proanthocyanidins, and soy flour and roasted soybean rich in isoflavones.

The two richest vegetable sources are black and green olives, which are particularly rich in tyrosols. They are followed by globe artichoke heads and red and green chicory (all rich in chlorogenic acid), onion (red or yellow), shallot and spinach (rich in flavonols). Other vegetables are found further down the list: broccoli, asparagus, potato, endive, lettuce, endive (escarole) and carrot.

The first beverage in the list is coffee (rich in chlorogenic acids), followed by black and green tea (rich in catechins, theaflavins and proanthocyanidins) and red wine (containing catechins, proanthocyanidins, anthocyanins and hydroxycinnamic acids). Several fruit juices are also found further down the list, containing lower amounts of polyphenols. The list also includes several cereals such as whole grain flours from wheat or rye, rich in ferulic acid and alkylresorcinols, and two plant oils (extravirgin olive oil rich in tyrosols and rapeseed oil containing 4-vinylsyringol).

The total polyphenol contents determined here using the Phenol-Explorer data can be compared with those published by Ovaskainen *et al.* (2008), who developed one of the most comprehensive polyphenol composition tables for 99 foods commonly consumed in Finland. A total of 33 of these foods were found among the 100 richest foods listed in this work. Polyphenol concentrations differed significantly between the two studies. In the study presented here, 11 of these 33 foods were found to have polyphenol concentrations that were more than twice as high as the Finnish values, whereas for five, the concentrations were half of those found in the Finnish list. It is not easy to explain these differences, as no details are given on the contents of individual phenolic compounds in the Finnish foods. However, some Finnish values appear surprisingly low: 1.1 mg per 100 g for onion or 2.2 mg per 100 g for brown beans, known for their high content of flavonols and flavanols, respectively (catechins and proanthocyanidins). Concentrations for other foods in the Phenol-Explorer might also be revised in the future as more data are published. For example, content values for coffee are based on no more than five original publications and could be revised as more data are published (Pérez-Jiménez *et al*., 2010). Furthermore, data for proanthocyanidins are still lacking for many foods, in particular fruits. This may result in a revision of the total polyphenol content of these foods as more data are published.

Some foods, such as spices and herbs, can be rich in polyphenols, but the amount consumed is low. Therefore, it is also important to estimate the amount of polyphenols in a serving (Table 2). Certain foods and beverages, such as several fruit juices and beer, do not appear in the list of foods richest in polyphenols (Table 1), but because the typical serving size is greater than 100 g, they appear in Table 2. The top 13 foods, when ranked by polyphenol concentration in a serving, are mainly fruits (seven berries and three other fruits), along with one vegetable (globe artichoke heads) and coffee. Black tea, green tea and red wine are also now higher up in the list (16th, 17th and 22nd positions). In contrast, some foods consumed in smaller amounts now appear further down the list. Dark chocolate and cocoa powder now appear at the 14th and 24th positions, instead of the 3rd and 8th positions, respectively. The same should be true for spices and herbs, although no ranking could be given because of the lack of data available on their serving size.

In summary, use of the Phenol-Explorer database on the polyphenol content of foods has established for the first time a ranking of the richest dietary sources of polyphenols based on a considerable amount of composition data published in the scientific literature. Such a ranking may be used as a reference to prioritise which foods should be studied in the future to evaluate the role of polyphenols in health and the prevention of diseases. However, limitations of the present data should not be overlooked. The total polyphenols concentration of a food is unlikely to fully explain any associated health effects because of the large differences in the bioavailability and biological activity of individual polyphenols (Manach *et al*., 2005; Williamson and Manach, 2005). These differences emphasise the value of using detailed content values for the 500 dietary polyphenols, as can be found in the Phenol-Explorer database.

Conflict of interest

A Scalbert has received payment as a member of the scientific advisory boards of Barry-Callebaut and McCormick Scientific Institute, for acting as a consultant for Coca-Cola and for speaking at the invitation of Unilever and Mars. He has received grant support from Danone, Nestlé and Unilever. The other authors declare no conflict of interest.

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