JOURNAL OF AGRICULTURAL AND FOOD CHEMISTRY
ARTICLE

J. Agric. Food Chem. 2010, 58, 4959–4969 4959
DOI:10.1021/jf100128b

Systematic Analysis of the Content of 502 Polyphenols in 452 Foods and Beverages: An Application of the Phenol-Explorer Database

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Considerable information on polyphenol content in foods is scattered in up to 1000 peer-reviewed publications and is therefore not easily exploited. Over 60000 food composition data have been collected from this literature and stored in the new Phenol-Explorer database (www.phenol-explorer.eu). Thirty-seven thousand data were selected after evaluation and aggregated separately according to 5 categories of analytical methods to generate mean content values for 502 compounds (glycosides, esters, or aglycones) in 452 foods. These data are exploited here in a first systematic analysis of the content in foods of these 502 polyphenols. These data will be useful for epidemiologists to determine polyphenol intake and associations with health and diseases in populations and for food scientitsts and food manufacturers to develop new products with optimized properties.

KEYWORDS: Polyphenols; flavonoids; phenolic acids; lignans; stilbenes; content in foods; database; Phenol-Explorer

INTRODUCTION

Polyphenols are widespread secondary metabolites found in various amounts in fruits, vegetables, cereals, and beverages such as wine, coffee, cocoa, and tea (*1*). They all have in common one or several phenol groups in their structure capable of reducing reactive oxygen species and other organic or nonorganic substrates. This property is at the origin of their widely documented antioxidant properties and of the considerable interest paid to their role in the prevention of chronic diseases such as cardiovascular diseases, cancers, type 2 diabetes, neurodegenerative diseases, or osteoporosis (*2*). About 1 g of polyphenols per day is commonly ingested with foods, and polyphenols are therefore the most abundant antioxidants in the diet (*3*).

In the study of their technological or biological properties, dietary polyphenols have often been considered globally using colorimetric assays such as Folin, FRAP, or ORAC to estimate the total content of polyphenols and other reducing compounds in foods (*4*−*6*). However, these global assays do not take into account the huge diversity of their chemical structures or their contrasting biological properties (*1*, *7*). Because of their different properties, it is essential to consider dietary polyphenols as individual chemical entities rather than as a whole undifferentiated group.

Several thousand polyphenols have been characterized in plants (*8*, *9*), and several hundreds of them are found in food plants. They belong to four main classes, flavonoids, phenolic acids, stilbenes, and lignans. They vary widely in their hydroxylation pattern and can be glycosylated and/or acylated. They range from simple molecules such as phenolic acids to highly polymerized compounds such as tannins.

Polyphenols are widely distributed in foods. All foods of plant origin contain some polyphenols in low or high amounts. It is important to know precisely the nature and the amounts of the various polyphenols contained in these foods and in the human diet to understand their potential role in the prevention of diseases and in health. The determination of their intake has not been an easy task as the information on their content in foods was until recently scattered in several hundreds of publications. The information was also difficult to exploit due to the diversity of the methods used for their estimation and the many factors known to influence their content in foods. These factors include plant varieties, environmental factors, agricultural practices, food processing, food storage, and cooking.

It is clearly beyond the capability of a single laboratory to provide reliable contents for all polyphenols in foods. This is why several authors have compiled the scientific literature and developed databases to make this information more easily accessible and exploitable. These databases differ by their coverage. Some are specific to a particular group of polyphenols such as isoflavones or lignans (*10*−*12*); others cover flavonoids or phenolic acids in general (*13*, *14*). The USDA database includes all types of flavonoids and contains composition data for 50 different flavonoid aglycones (*15*−*17*). EuroFIR-BASIS is another database currently developed on bioactives that includes original content values for various polyphenols in plant-based foods (*18*). The more recently published Phenol-Explorer database includes content data for 502 polyphenols, flavonoids, phenolic acids, lignans, and stilbenes in 452 foods (*19*). Over 60000 composition data published since 1969 have been systematically collected, evaluated, and

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Published on Web 03/19/2010

stored in the database. Data obtained by five different types of analytical methods have been aggregated separately to provide mean content values for each polyphenol in the various foods. Both the USDA and Phenol-Explorer databases allow the original literature sources used to calculate these mean content values to be traced. The USDA database is available as an open access text file on the USDA Website. The Phenol-Explorer database is available as an open access electronic source and can be searched by food or chemical name on a user-friendly Website, and all data can be exported as Excel files (www.phenol-explorer.eu).

This paper describes the polyphenols contained in the Phenol-Explorer database, glycosides, esters, or aglycones of the various structural classes or subclasses and their content in the main foods and beverages. Composition data obtained by the different categories of analytical methods are compared.

MATERIALS AND METHODS

The development of the Phenol-Explorer database included five main steps: literature search, data compilation in an Access database, data evaluation, data aggregation to produce weighted mean polyphenol content values, and final data exportation to a MySQL database, freely available as a user-friendly Web interface (www.phenol-explorer.eu). The development of the database has been fully described elsewhere (*19*).

Collection and Evaluation of Composition Data from Literature Sources. The literature search for composition data of polyphenols in foods and beverages was performed using the FSTA database (Food Science and Technology Abstracts) (1969−2009). A list of foods was established on the basis of existing food ontologies (*20*) and reference sources for dietary polyphenols (*21*), and queries were done for the different food groups. Queries were built from a template using the most representative food names in the food group of interest, associated with the names of polyphenols and polyphenol classes and with keywords related to quantitative information (such as "composition", "content", "determination", or "quantification"). The bibliographical references were imported in an Endnote 7.0 (Thomson Reuters) library. The references susceptible to providing quantitative information on polyphenols in the studied food groups were selected on the basis of their title and abstract. The corresponding full papers were collected. The comprehensiveness of the literature search was checked by examination of the citations in the collected articles, as well as in review papers and books and in existing databases (*15*−*17*).

A total of 1300 scientific papers was thus collected. Food composition data were finally extracted from 901 of these publications. All details given in the publications on the foods analyzed (species and cultivar, plant part, commercial origin, sampling conditions, food processing...), the phenolic compounds quantified, the extraction conditions, and the analytical methods were stored in a Microsoft Office Access 2000 database. Specific ontologies were created for foods and for polyphenols. Content data in the publications were critically evaluated by applying a set of inclusion/exclusion criteria relative to sampling, polyphenol analysis, and their documentation in the publication (*19*). The principal reasons for excluding data from the database were (1) lack of information on the nature of the samples analyzed, inedible part of the plant; (2) for processed foods, processing method different from regular practice; (3) unknown moisture content of the samples (for content values expressed per dry weight units); (4) unknown number of samples for content values reported as mean values in the original publication; (5) inappropriate method of analysis (e.g., a number of spectrophotometric or colorimetric methods); (6) insufficient description of the analytical method; (7) inaccurate identification of the polyphenol or lack of details to justify the proper identity of the estimated compound; and (8) inappropriate standard for quantification.

Data Aggregation To Produce Weighted Mean Values. Data that passed all selection criteria were aggregated to produce weighted mean content values according to the number of independent samples used to produce each original content value. Separate aggregations were made according to five types of analytical methods previously defined: chromatography, chromatography with hydrolysis, Folin assay (total polyphenols), pH differential method (total anthocyanins), and normal phase HPLC (proanthocyanidins).

Some polyphenols considered separately in the original literature sources were regrouped and mean content values calculated as follows:

Insoluble Phenolic Acids. Phenolic acids can be present in foods in different forms: some are soluble and present as free phenolic acids, esters, or glycosides and are usually directly analyzed by chromatography. Others are insoluble and esterified to cell wall polymers as in cereals. They are usually estimated by acid or base hydrolysis of the ester bonds after first removing soluble phenolic acids by extraction with solvents (*22*). In Phenol-Explorer, the phenolic acid contents displayed when selecting the method "chromatography after hydrolysis" are the calculated sum of the contents of all esters (soluble and insoluble) and free phenolic acids.

Proanthocyanidins are commonly analyzed by using two different methods. Reverse phase HPLC allows one to estimate dimers and trimers. Proanthocyanidins of higher polymerization degree can only be separated by normal phase HPLC according to their polymerization degree (*23*). Contents measured by this last method are thus expressed per individual degree of polymerization rather than individual compounds, which cannot be separated and identified. In Phenol-Explorer, five categories of proanthocyanidins were made: dimers, trimers, 4−6-mers, 7−10-mers, and polymers as used in the USDA database (*15*).

Isomers and Enantiomers. The contents of cis and trans isomers of cinnamic acids and stilbenes are not given separately but as a total in Phenol-Explorer. Indeed, these isomers can be converted from one form to the other following exposure to UV light or heat treatment (*24*−*26*), factors not necessarily controlled during the preparation of the samples, extraction, and analysis. Similarly, some phenolic compounds can also be present in different enantiomeric forms (flavanols, lignans). For example, (−)-epicatechin is partially epimerized to (−)-catechin during cocoa processing (*27*). With regard to lignans, two secoisolariciresinol diglucoside diastereomers were identified, the [2*R*,2′*R*]-2,3-bis[(4-hydroxy-3-methoxyphenyl)-methyl]-1,4-butanediyl-bis-β-glucopyranoside, and the minor [2*R*,2′*S*]-2,3-bis[(4-hydroxy-3-methoxyphenyl)methyl]-1,4-butanediyl-bis-β-glucopyranoside (*28*). However, these enantiomers have very rarely been analyzed separately. For this reason, no distinction is made in the database between them.

The content values displayed in Phenol-Explorer are expressed in standard units (mg/100 g of fresh weight and mg/100 mL) after conversion of the original units (ppm, mg/kg, mol, ...) found in the publications. For foods of low moisture content dried before analysis (principally cereals), the content values expressed per dry weight units were converted to be expressed per fresh weight units using the moisture contents provided in the publication. For some cereal products of low moisture content (e.g., flour, raw pasta, semolina, or grain) the original moisture content was not available and a standard value was used to make these conversions (*29*).

The use of proper standards is important for the valid identification and quantification of polyphenols. The standards used for quantification can be different from the studied compound itself, particularly when no authentic standard is available, and content values can be expressed as equivalents of the standard used for quantification, for example, resveratrol glucosides expressed as resveratrol, phloretin 2′-*O*-xylosyl glucosides and other related compounds expressed as phloridzin equivalents, or hydroxytyrosol expressed as tyrosol equivalents. Content values for a given compound expressed in equivalents of a related compound used as a standard for quantification were recalculated on the basis of their molecular weights.

RESULTS

Food Classification. Foods were classified in nine groups and various subgroups taking as a reference the food indexing systems LanguaL and Eurocode2 (*30*) (**Table 1**). Each item is described by a combination of a general food name (e.g., "orange") eventually subdivided according to cultivars and processing into several food types ("orange [blond]" or "orange [blood]), associated with various tags (e.g. "orange [blond], juice from concentrate" or "orange [blond], pure juice"). The creation of a food type or tag depended on the number of composition data available. Often no

Table 1. Food Classification in Phenol-Explorer

food group	food subgroups	no. of items
nonalcoholic beverages	cocoa beverage; Arabica coffee beverages; Robusta coffee beverages; unknown coffee beverages; berry juices; citrus juices; drupe juices; pome juices; tropical fruit juices; herb infusions; soy drinks	65
alcoholic beverages	beers; ciders; grape wines; berry wines; sparkling wines; fortified wines; liquors; brandy; rum; whiskey	19
fruits and fruit products	berries; citrus; drupes; gourds; pomes; tropical fruits; stalk vegetables; other fruits; dried berries; berry jams; drupe jams; pome jams	103
vegetables	cabbages; Chinese cabbages; fruit vegetables; gourds; leaf vegetables; onion-family vegetables; pod vegetables; pulse vegetables; root vegetables; shoot vegetables; stalk vegetables; tubers	72
cereals and cereal products	cereals; cereal products	21
seeds	nuts; common beans; other beans; lentils; peas; other seeds; soy and soy products	65
cocoa	chocolate; cocoa powders	3
seasonings	herbs; spices; spice blends; other seasonings	87
oils	cereal oils; fruit vegetable oils; nut oils; other seed oils	10

Table 2. Polyphenol Classification in Phenol-Explorer and Number of Aglycones, Glycosides, and Esters in Each Class

		no. of compounds			
polyphenol class	polyphenol subclasses	total[a]	aglycones	glycosides	esters
flavonoids	anthocyanins; chalcones; dihydrochalcones; flavanols; flavanones; flavones; flavonols; isoflavonoids	277	59	191	63
phenolic acids	hydroxybenzoic acids; hydroxycinnamic acids; hydroxyphenylacetic acids; hydroxyphenylpropanoic acids	108	47	14	55
stilbenes	(no subclass)	10	8	2	0
lignans	(no subclass)	30	29	1	0
other polyphenols	alkylmethoxyphenols; alkylphenols; curcuminoids; furanocoumarins; hydroxybenzaldehydes; hydroxybenzoketones; hydroxycinnamaldehydes; hydroxycoumarins; hydroxyphenylpropenes; methoxyphenols; naphthoquinones; phenolic terpenes, tyrosols; other polyphenols	80	70	6	4

[a] Some compounds are both esterified and glycosylated; hence, the total number of compounds may be different from the sum of glycosides, esters, and aglycones.

Table 3. Categories of Analytical Methods, Polyphenols Analyzed by Each Type of Method, and Number of Original Content Data Used To Produce Mean Content Values

aggregated method	analyzed compounds	no. of original content data
chromatography	flavonoids; phenolic acids; stilbenes	28739
chromatography after hydrolysis	flavonoids; phenolic acids; lignans	5804
Folin assay (spectrophotometric)	total polyphenols	2218
pH differential method (spectrophotometric)	anthocyanins	409
normal phase HPLC	proanthocyanidins according to degree of polymerization	488

distinction was made between, for example, blond orange varieties due to the paucity of data on each specific variety. However, specific groups of cultivars were eventually made if well recognized by the consumers and clearly different in their polyphenol profiles ("orange [blond]" and "orange [blood]").

Compound Classification. Table 2 shows the classification adopted for the 502 phenolic compounds, which was derived from reference books and online chemical databases (*8*, *31*, *32*). The compound names used in Phenol-Explorer are the ones most commonly used in the literature (e.g., "hesperidin" and not "hesperetin 7-*O*-rutinoside"). Synonyms are also provided. Nearly 80% of flavonoids are glycosides, and more than half of the phenolic acids are esters.

Comparison of Analytical Methods. There is no unique method to analyze the various classes of polyphenols in foods. Not all methods used for polyphenol quantification can be considered reliable. A selection was made, and methods were grouped into five categories (**Table 3**). Methods from the two first categories (chromatography and chromatography after hydrolysis) are used to estimate individual phenolic compounds, either directly (glycosides, esters, and aglycones) or after hydrolysis with an acid, a base, or an enzyme (aglycones). Such hydrolyses have been applied to some flavonoids to limit the complexity of the polyphenol mixture to be analyzed. They have also been applied to phenolic acids and lignans bound to the insoluble food matrix to solubilize them before analysis. Flavonols are the polyphenol subclass for which more content values after hydrolysis were compiled (2399 data), followed by hydroxycinnamic acids (1131 data), flavones (747 data), hydroxybenzoic acids (543 data), lignans (344 data), isoflavonoids (235 data), and flavanones (162 data).

The three other methods allow one to determine groups of polyphenols. The Folin assay is used to estimate "total polyphenols". However, the method is well-known to interact with other reducing compounds such as ascorbic acid also present in foods. Folin values should therefore be considered as estimates of the total content of reducing compounds, rather than of total polyphenols. Total anthocyanins are often estimated by the pH-differential colorimetric method. Proanthocyanidins have been estimated by normal phase HPLC (*23*). This last method allows one to estimate not only dimers or trimers (also commonly estimated by reverse phase HPLC) but also higher oligomers, which cannot be separated by reverse phase HPLC. Oligomers are globally estimated per degree of polymerization (dimers, trimers, ..., up to decamers).

Original content values were aggregated within each method category to provide the mean content values. The large number of values for each category of method (**Table 3**) allows one to compare mean content values obtained by methods from the different categories. Content values obtained by colorimetric assays (Folin assay for total polyphenols or pH-differential method for anthocyanins) will be discussed in a separate paper (Perez-Jimenez, Neveu, Vos, and Scalbert, submitted for publication).

The sum of individual polyphenols measured by chromatography, either directly or after hydrolysis of the glycosides or

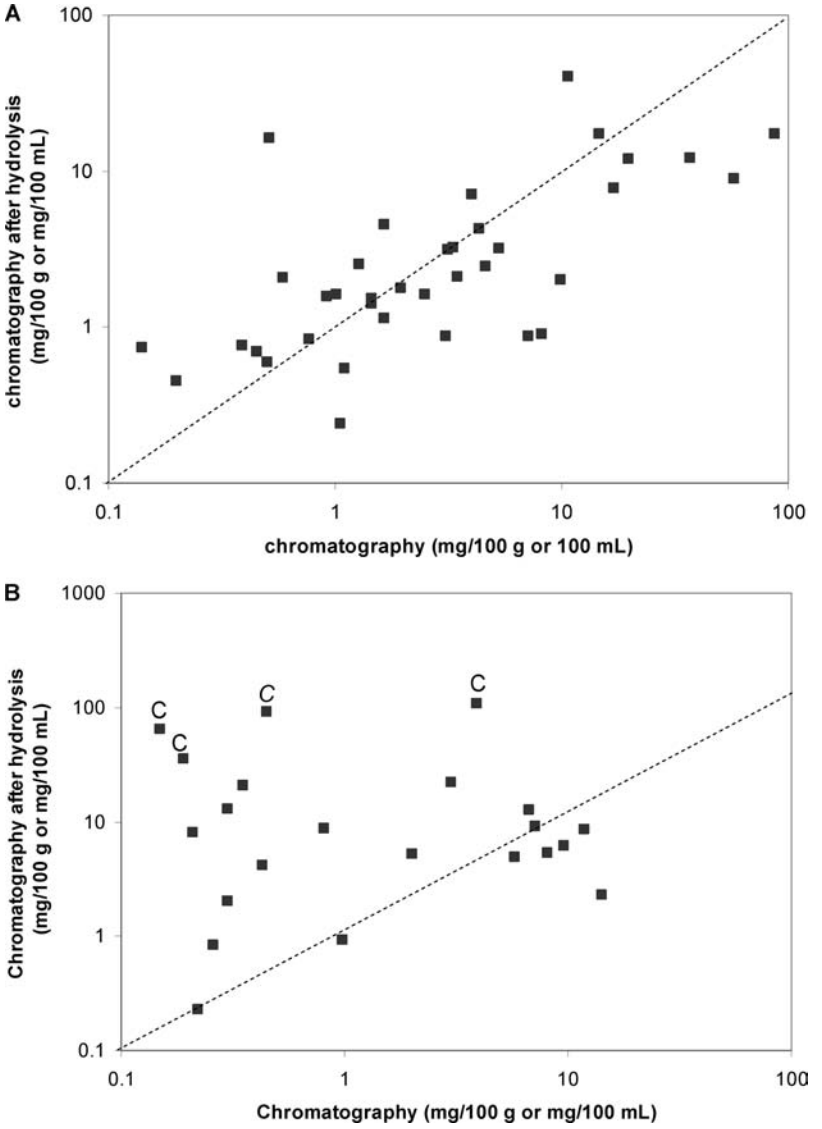

Figure 1. Comparison of polyphenol mean content values in various foods as obtained by chromatography without or after hydrolysis: (**A**) quercetin; (**B**) ferulic acid. Contents obtained by chromatography are expressed in aglycone equivalents. C, whole-grain cereals.

esters, can be compared. Both types of data are well correlated (**Figure 1A**). However, some discrepancies are observed when individual total values are considered. It can be explained either by an insufficient number of data, which cannot erase the effect of the variability of content between samples. When a relatively low value is measured after hydrolysis, it could also be explained by some degradation of the aglycones during hydrolysis (*33*) and the inappropriate or lack of correction for this loss. In constrast, values obtained after hydrolysis can also be much higher than those obtained without hydrolysis when a significant fraction of the polyphenol is bound to the food matrix in an insoluble form. This is particularly seen for whole-grain cereals known to be rich in ferulic acid esterified to cell wall hemicelluloses (**Figure 1B**). The content data collected in Phenol-Explorer show that 96−99% of the ferulic acid present in whole -grain wheat, rice, rye, and maize can only be estimated after hydrolysis of the ester bond (not shown).

Content values obtained by the two types of methods used for the estimation of proanthocyanidins (individual compounds by chromatography or proanthocyandins according to their polymerization degree by normal phase HPLC) can be compared for dimers and trimers (**Figure 2**). Content values were generally higher when determined by normal phase HPLC, but more data obtained by direct HPLC would be needed to allow a proper comparison between the two methods.

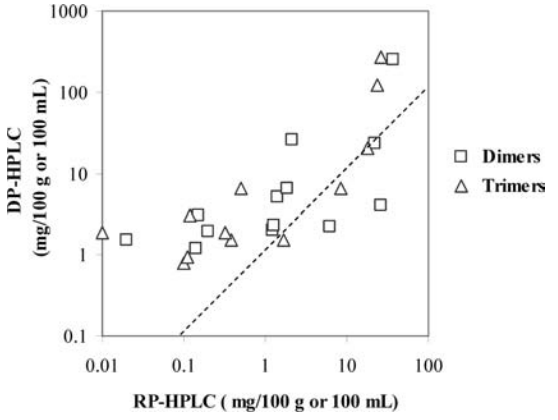

Figure 2. Comparison of proanthocyanidin dimer and trimer content values in various foods as obtained by reverse phase (RP) or direct phase (DP) HPLC.

Number of Food Composition Data. A total of 60832 food composition data were collected from 901 scientific publications.

The majority of these publications (95%) appeared in food science journals in the past 20 years and 70% in the past 10 years. The quality of these data was evaluated on the basis of a set of specified criteria (see Materials and Methods). Finally, 37634 food composition data originating from a total of 638 publications were selected to calculate mean content values for 502 polyphenols in 452 foods.

Among the 452 foods included in Phenol-Explorer, some have been more extensively studied for their polyphenol content than others. The three foods with the highest number of original composition data are red wine (3346 data), virgin olive oil (1852 data), and black tea infusion (1136 data). Three other beverages, beer, white wine, and green tea infusion, are also well documented with, respectively, 791, 571, and 548 data. A large number of data were found for fruits and more particularly for some berries (strawberry, red raspberry, highbush blueberry, blackberry), apple, and plum, each with over 500 original composition data. Some vegetables were also well studied: broccoli, tomato, black olive, spinach, green lettuce, and yellow onion with 300−500 composition data per food.

The number of composition data also varies widely according to the phenolic compounds. The ones with more data are flavonols and more specifically quercetin (1635 data), kaempferol (944 data), myricetin (870 data), rutin (529 data), quercetin-3-*O*-glucoside (349 data), and quercetin-3-*O*-galactoside (321 data). Many data were collected for flavanols and particularly for (−)-epicatechin (1010 data), (+)-catechin (966 data), and (−)-epicatechin-3-*O*-gallate, (−)-epigallocatechin 3-*O*-gallate, (−)-epigallocatechin, and procyanidin dimer B2 with 340−380 data each. Other well-studied polyphenols are the phenolic acids including *p*-coumaric acid (909 data), 5-caffeoylquinic acid (851 data), caffeic acid (796 data), ferulic acid (702 data), and gallic acid (525 data). Numerous data were found for tyrosol (369 data), hydroxytyrosol (277 data), two anthocyanins, cyanidin 3-*O*-glucoside (327 data) and malvidin 3-*O*-glucoside (212 data), and the isoflavones genistein (243 data) and daidzein (231 data).

The number of content data collected for each polyphenol reflects the interest of the scientists for a given phenolic compound and not necessarily the abundance of this compound in the diet. A considerable number of data are available for some low-abundance compounds such as resveratrol (478 content values in red wine, with a mean concentration of 0.27 mg/100 mL) or certain polyphenols in olive oil (121 content values for vanillic acid, with a mean concentration of 0.12 mg/100 g). On the other hand, there is a paucity of content data on more abundant polyphenols, either for rich sources such as coffee (no more than four original content values for each caffeoyl ester), strawberry, or largely consumed sources such as potato (two publications with large discrepancies in the content of 5-caffeoylquinic acid) or orange (flavanone contents are available for only orange juice). Phenol-Explorer allows one to easily identify the food sources for which data are insufficient.

Polyphenol Content of Foods. A general view on both the distribution and content of the various polyphenols in all major foods consumed with the human diet can be derived from the Phenol-Explorer data. The diversity of polyphenols varies between food groups. Over 150 polyphenols are found in each of the three following food groups: nonalcoholic beverages, fruits, and vegetables. Between 45 (cocoa products) and 147 (alcoholic beverages) compounds have been described in any of the other food groups (**Table 4**). Herbs and spices in the seasoning group often contain very high concentrations of phenolic compounds. However, they are consumed in low amounts and their contribution to the total polyphenol intake is therefore limited.

Table 4. Number of Polyphenols Described in Each Food Group

food group	flavonoids	phenolic acids	stilbenes	lignans	other polyphenols
nonalcoholic beverages	105	49	6	2	12
alcoholic beverages	75	33	13	7	19
fruits	112	47	7	6	1
vegetables	92	51	0	6	12
cereals	33	29	0	6	2
seeds	76	16	3	18	4
cocoa	25	13	2	0	5
seasonings	62	29	1	0	25
oils	11	28	2	12	22

Polyphenol distribution and content in herbs and spices will be discussed in a separate paper.

When the different polyphenol subclasses are considered separately, it appears that some of them, such as flavanols, flavonols, hydroxycinnamic acids, and hydroxybenzoic acids, are present in a large number of foods (between 93 and 145 foods for each of these subclasses), whereas the distribution of polyphenols from other subclasses is more limited (anthocyanins, isoflavonoids, flavanones, and stilbenes present in, respectively, 38, 27, 26, and 24 foods). Comparison of the total content of each polyphenol subclass shows that some classes are generally present in higher quantities (anthocyanins and flavanols) than others (**Table 5**). Other classes are present in lower amounts (flavonols, flavones) or very low amounts (stilbenes). The high mean content for lignans is explained by the low number of foods containing lignans, with several of them in very high amounts. Many foods contain traces of lignans bound to the matrix, which are estimated after hydrolysis. These values were not taken into account to calculate the mean contents in foods as appears in **Table 5**. Examples of foods richest in each of the different subclasses are also given in **Table 5**.

When the content of individual polyphenols is considered, it appears that 56% of them are only present as traces with contents not exceeding 1 mg/100 g or 1 mg/100 mL whatever the food considered. Conversely, some individual polyphenols may be present in very high concentrations in some specific foods. The first most abundant compounds are cyanidin 3-*O*-glucoside in black elderberry (794 mg/100 g), ellagic acid in chestnut (735 mg/100 g), gallic acid in chestnut (480 mg/100 g), cyanidin 3-*O*-sambubioside in black elderberry (463 mg/100 g), 5-caffeoylquinic acid in sunflower seed meal (454 mg/100 g), sesamin in sesame oil (420 mg/100 g), stigmastanol ferulate in maize bran oil (360 mg/100 g), delphinidin 3-*O*-rutinoside in black currant (304 mg/100 g), and sesamolin in black sesame seed oil (287 mg/100 g). The occurrence of individual polyphenols may be limited to specific foods, such as phloretin in apple, avenanthramides in oat, or oleuropein and ligstroside in olive, whereas others are present in a large number of foods. For example, (+)-catechin, caffeic acid, and ferulic acid are present in, respectively, 84, 76, and 75 foods.

The inclusion of glycosides and esters in Phenol-Explorer makes the database unique as compared to previous databases containing only aglycones. The proportions of glycosides, esters, and aglycones are quite different in the various polyphenol classes and subclasses. **Table 6** shows the distribution of these forms in a selection of major food sources for each polyphenol subclass. Anthocyanins, flavanones, flavones, flavonols, and isoflavonoids are present mainly as glycosides, whereas phenolic acids appear mainly as esters. The proportion of the different isoflavonoid forms in different soy foods shows that processing leads to a reduction of the concentrations of esters and glycosides and to an increase of those of aglycones.

Table 7 shows the ranges of concentration for the various polyphenol (sub)classes in the main foods containing more than

Table 5. Mean Contents in Foods for the Different Polyphenol Subclasses

polyphenol subclass	content in foods[a,b] (mean ± SD, mg/100 g or mg/100 mL)	richest foods for the polyphenol subclass (content)
anthocyanins	115 ± 259	black elderberry (1316), black chokeberry (878), black currant (595)
flavanols	180 ± 560[c]	cocoa powder (3410), dark chocolate (1589), hazelnut (495)
flavanones	23 ± 25	pure blood orange juice (51), pure grapefruit juice (46), pure blond orange juice (38)
flavones	4 ± 12	whole-grain common wheat flour (73), globe artichoke heads (58), black olive (27)
flavonols	11 ± 21	red onion (158), spinach (119), shallot (112)
isoflavonoids	66 ± 106	soy flour (466), roasted soy bean (246), soy tempe (148)
hydroxybenzoic acids	29 ± 121	chestnut (1215), walnut (449), red raspberry (121)
hydroxycinnamic acids	35 ± 78	coffee (278), red chicory (203), globe artichoke heads (202)
stilbenes	0.7 ± 1.1	red wine (3.4), lingonberry (3.0), red currant (1.6)
lignans	550 ± 625	sesame seed oil (1294), flaxseed meal (867), sesame seed meal (776)

[a] Contents measured by chromatography with no previous hydrolysis of the glycosides and esters. Foods containing no polyphenol from the subclass considered are excluded. [b] Spices are not considered here. [c] Either sum of catechins and proanthocyanidin dimers and trimers (determined by chromatography), or sum of catechins (determined by chromatography) and proanthocyanidin oligomers (determined by direct phase HPLC) when available.

Table 6. Distribution of Aglycones, Glycosides, and Esters in a Selection of the Richest Food Sources for the Different Polyphenol Subclasses

		content[b] (% total in the subclass)			no. of compounds		
polyphenol (sub)class	food[a]	aglycones	glycosides	esters	aglycones	glycosides	esters
anthocyanins	black elderberry	0	100	3	0	6	1
	black chokeberry	0	100	0	0	5	0
	black currant	0	100	1	0	9	2
flavanols[c]	cocoa powder	99	0.01	0	6	1	0
	dark chocolate	99	0.3	0	5	1	0
	hazelnut	99	0	0.3	3	0	2
flavanones	pure blood orange juice	0	100	0	0	3	0
	pure grapefruit juice	3	97	0	1	8	0
	pure blond orange juice	0	100	0	0	6	0
flavones	black olive	12	88	0	1	4	0
	pure blond orange juice	85	15	0	4	1	0
	pure lemon juice	0	100	0	0	2	0
flavonols	red onion	5	95	0	2	6	0
	black olive	0	100	0	0	2	0
	spinach	0	100	45	0	9	5
isoflavonoids	soy flour	1	99	58	3	9	3
	soy nut	7	93	45	3	9	3
	soy paste (natto)	7	93	7	3	9	3
hydroxybenzoic acids	American cranberry	100	0	0	5	0	0
	red raspberry	1	2	99	1	3	5
	black olive	100	0	0	7	0	0
hydroxycinnamic acids	sunflower seed, meal	2	0	98	1	0	1
	coffee	0.01	0	99	1	0	9
	globe artichoke heads	0	0	100	0	0	1
stilbenes	red wine	53	47	0	5	2	0
	white wine	7	93	0	3	2	0
	green grape	8	92	0	1	1	0
lignans	black sesame seed oil	100	0	0	5	0	0
	sesame seed oil	100	0	0	7	0	0
	refined olive oil	100	0	0	2	0	0

[a] Spices are not considered in this table. [b] Totals higher than 100% come from the fact that some polyphenols may be at the same time glycosides and esters (e.g. cyanidin 3-*O*-(6′′-caffeoylglucoside). [c] Values are either sum of catechins and proanthocyanidin dimers and trimers (determined by chromatography), or sum of catechins (determined by chromatography) and proanthocyanidin oligomers (determined by direct phase HPLC) when available.

1 mg/100 g or 1 mg/100 mL polyphenols in the considered (sub)class. Anthocyanins are particularly abundant in red fruits, with highest concentrations in dark-colored fruits such as a number of berries, cherry, or black olive. Highest concentrations were found in black elderberry (1316 mg/100 g), black chokeberry (878 mg/100 g), and black currant (595 mg/100 g). Apart from berries and fruits, other sources of anthocyanins are red wine and to a lesser extent rosé wine, colored beans, and specific varieties of

Table 7. Food Classification According to the Contents in the Various Polyphenol (Sub)classes

	total concentration of the polyphenol (sub)class (mg/100 g or mg/100 mL)						
	1−5	5−20	20−40	40−60	60−80	80−100	>100
flavonoids							
anthocyanins	pure blood orange juice cloudberry gooseberry red lettuce red onion	pure pomegranate juice	red wine red currant black bean	American cranberry lingonberry plum	black grape red raspberry strawberry	black olive	black chokeberry black elderberry blackberry black currant blueberry sweet cherry
dihydrochalcones	pure apple juice	apple					
dihydroflavonols		red wine					
flavanols	pure pear juice[a] white wine[a] rosé wine[a] cloudberry[a] pear[b] persimmon[a] green bean[a] cashew nut	sherry[a] chocolate beverage red raspberry[a] sweet cherry[a] nectarine[a] banana kiwi mango avocado date, fresh quince[a] lentils[a] roasted peanut	pure apple juice[a] black elderberry blackberry apricot	red wine red currant peach[a]	black tea[a] green tea[a] black grape walnut	green grape	black currant blueberry strawberry plum apple almond hazelnut pecan nut pistachio dark chocolate cocoa powder
flavanones		pure pummelo juice pure lime juice	pure lemon juice pure blond orange juice	pure grapefruit juice pure blood orange juice			
flavones	pure lemon juice red lettuce extra virgin olive oil	pure orange blond juice lemon verbena tea		black olive globe artichoke heads		whole-grain common wheat flour	
flavonols	pure apple juice bilberry black grape green grape strawberry apricot zucchini lettuce white onion green bean almond hazelnut	black tea green tea red wine plum blackberry black currant red lettuce pistachio pecan nut black bean	American cranberry blueberry lingonberry curly endive escarole endive broad bean pod asparagus broccoli whole-grain buckwheat flour dark chocolate			black chokeberry yellow onion	spinach red onion shallot
isoflavonoids	soy sauce	soy milk soybean sprouts soy cheese	soy tofu		soy meat	soy yogurt soy milk powder	soy flour soy tempe roasted soybean
phenolic acids							
hydroxybenzoic acids	pure American cranberry juice pure apple juice beer rosé wine white wine sherry cognac Scotch whiskey black currant gooseberry blueberry banana pumpkin red onion whole-grain rye flour[b]	green tea black tea red wine blackberry strawberry cloudberry fresh date dried date green olive	red chicory	American cranberry blackberry pomegranate juice black olive green chicory			red raspberry chestnut walnut[b]

Table 7. Continued

	total concentration of the polyphenol (sub)class (mg/100 g or mg/100 mL)						
	1−5	5−20	20−40	40−60	60−80	80−100	>100
hydroxcinnamic acids	black tea green tea white wine champagne sherry bilberry cloudberry gooseberry green grape red currant cauliflower tomato pumpkin lettuce yellow onion refined buckwheat flour[b] rapeseed oil	pure apple juice pure pear juice pure orange juice[b] red wine rosé wine blackberry strawberry lingonberry black currant apricot nectarine peach apple pear quince fresh date broccoli carrot refined common wheat flour[b] refined rice[a] whole-grain rice flour[b] roasted peanut lentils	dried date dark chocolate cocoa powder lemon verbena tea potato refined rye flour[b] whole-grain rice[b] white bean[b] black bean[b]		whole-grain common wheat flour[b] hard wheat semolina[b]	plum cherry black olive American cranberry[b]	coffee black chokeberry blueberry prune green olive green chicory red chicory globe artichoke heads[b] whole-grain maize[b] whole-grain rye flour[b]
hydroxyphenylacetic acids		black olive green olive					
stilbenes	red wine lingonberry red currant						
lignans	extra virgin olive oil refined olive oil virgin olive oil whole-grain buckwheat flour[a,b] whole-grain rye flour[b]						flaxseed meal[b] sesame seed meal sesame seed oil
other polyphenols							
alkylphenols	refined common wheat flour refined rye flour pasta	rapeseed oil	whole-grain bread whole-grain pasta muesli		whole-grain common wheat flour whole-grain rye flour		bran breakfast cereals
alkylmethoxyphenols	coffee						
furanocoumarins	celery stalks						
tyrosols	red wine rosé wine champagne vinegar	sherry	refined olive oil	extra virgin olive oil virgin olive oil			black olive green olive

[a] The actual flavanol content in these foods may be higher as no data are available for oligomers of polymerization degree higher than trimers. [b] Data obtained by chromatography after hydrolysis.

colored fruits and vegetables such as blood orange, red lettuce, or red onion.

The richest sources for flavanols are cocoa (3411 mg/100 g) and dark chocolate (1590 mg/100 g). Berries are also very rich in flavanols with contents of 659, 330, and 139 mg/100 g for, respectively, black chokeberry, blueberry, and black currant. Other rich sources are strawberry (148 mg/100 g) and apple (111 mg/100 g) as well as nuts such as hazelnut, pecan nut, pistachio, and almonds (181−496 mg/100 g). Black tea, green tea, and red wine are also important sources of flavanols. A number of content values for flavanols are underestimated (marked by a footnote in **Table 7**). Indeed, for some foods only the contents of catechin monomers and proanthocyanidin dimers and trimers are available (as estimated by reverse phase HPLC), whereas values for higher oligomers (as determined by normal phase HPLC) are still missing.

The highest concentrations of flavonols were measured in onions (yellow and red) and shallot (73−158 mg/100 g), spinach (119 mg/100 g), and black chokeberry (88 mg/100 g). Flavonols are also present in a number of other foods and notably green

tea, black tea, dark chocolate, and various fruits, vegetables, and nuts.

Other flavonoid subclasses are found in a more limited number of food sources. Dihydrochalcones (phloretin glycosides) are present in apple (5.5 mg/100 g) and dihydroflavonols (dihydroquercetin and dihydromyricetin glycosides) in wine (5.4 mg/100 mL in red wine). The main sources of flavanones are citrus fruits. Contents in pure juices of grapefruit, orange, and lemon are, respectively, 46, 38, and 33 mg/100 mL. Many fewer data are available for citrus fruits (only content values for flavanone aglycones as obtained by chromatography after hydrolysis are available). Only traces of flavanones have been measured in other food sources such as beer, wine, or tomato. The main sources of flavones are celery leaves, red chicory, globe artichoke, black olive, and citrus fruits. Isoflavonoids are found in soy foods. Soy flour, soy nuts, and tempe are the richest sources of isoflavones, with contents > 100 mg/100 g.

Phenolic acids are widely distributed among foods. The main hydroxybenzoic acids are gallic acid (in various nuts, chicory, some berries, tea, and wine), ellagic acid (in various nuts and berries), 4-hydroxybenzoic acid (in olive, loquat, some berries, and carrot), vanillic acid (in date, some berries, olive, rye flour, Swiss chard, and cocoa), and syringic acid (in nuts, olive, date, pumpkin, and cauliflower). They are present as free form, esters, or glycosides. 5-*O*-Galloylquinic acid is present in tea, and gallic acid and ellagic acid glucosides are present in pomegranate juice. Gallic acid and ellagic acid are also esterified in ellagitannins, such as punicalagin in pomegranate juice or sanguiin H-6 and lambertianin C in raspberry. Highest concentrations of hydroxybenzoic acids were found in chestnut (1215 mg/100 g), raspberry (121 mg/100 g), pomegranate juice (55 mg/100 g), and blackberry (50 mg/100 g). Other notable sources are tea, wine, date, and a number of other berries.

Hydroxycinnamic acids are also widespread in foods. The most common phenolic acids are caffeic, ferulic, *p*-coumaric, and sinapic acid. Caffeic acid is largely present as quinic acid esters (chlorogenic acids) in coffee, various berries, various pome and drupe fruits (plum, sweet cherry, apple, peach, pear, nectarine, quince, and apricot), a number of vegetables (globe artichoke heads, chicory, carrot, broccoli, lettuce, and tomato), olive, and potato. Caffeic acid is also present as esters with sugars (verbascoside in olive and verbena) and tartaric acid (chicoric acid and caffeoyltartaric acid) in chicory, grape, and wine. Caffeic acid glucosides are found in some berries. Free caffeic acid is often associated with caffeoyl esters but in relatively low concentrations. Ferulic acid is mainly found as esters with quinic acid in coffee, with hemicelluloses in cereals and with anthocyanins in berries and wine. It is also glucosylated in flaxseed meal. *p*-Coumaric acid is present as quinic acid esters in sweet cherry and apple and in free form in olive. Sinapic acid is present in free form in olive and cauliflower.

Highest concentrations of hydroxycinnamic acids are found in coffee (212 mg/100 mL), globe artichoke heads (202 mg/100 g), prune (192 mg/100 g), red chicory (183 mg/100 g), highbush blueberry (135 mg/100 g), green chicory (108 mg/100 g), green olive (104 mg/100 g), black olive (96 mg/100 g), plum (89 mg/100 g), and sweet cherry (88 mg/100 g). In cereals, highest hydroxycinnamate contents (determined after hydrolysis of the cinnamoyl esters) are observed in whole maize grain (212 mg/100 g), whole-grain rye flour (136 mg/100 g), and refined wheat flour (90 mg/100 g).

Two types of seeds are very rich in lignans: sesame seed and flaxseed. Lignan contents in sesame oil and meal and in flaxseed meal are, respectively, 1295, 776, and 867 mg/100 g. All other sources contain no more than 3 mg/100 g lignans. With the exception of sesame oil and meal, olives, and olive oils, lignans are most often bound to complex organic molecules and require a hydrolysis step to be solubilized and quantified. However, with the exception of flaxseed, the content of these bound lignans remains low and does not exceed 1 mg/100 g whatever the food considered.

Other polyphenols present in significant amounts in foods are alkylresorcinols and tyrosols. Alkylresorcinols are characteristic of cereals. Highest contents are found in breakfast cereal bran (286 mg/100 g), rye whole-grain flour (69 mg/100 g), and common wheat whole-grain flour (64 mg/100 g). Tyrosols are mainly present in olive and olive oil, with contents as high as 266 mg/100 g in black olive and 60 mg/100 g in extra virgin olive oil. The main compounds are oleuropein and its aglycone. A number of minor polyphenols occur in low amounts in specific foods. To mention just some of them, resveratrol 3-*O*-glucoside, a stilbene, is present in red wine (0.6 mg/100 mL), juglone, an anthraquinone, in walnut (11.7 mg/100 g), arbutin, an hydroquinone, in pear (1.4 mg/100 g), and bergapten, a furanocoumarin, in celery stalk (1.1 mg/100 g).

DISCUSSION

Increasing interest in food polyphenols and their effects on health has led to the development of several databases on polyphenol contents in foods. The most significant ones have been so far the USDA databases on flavonoids (*16*), proanthocyanidins (*15*), and isoflavonoids (*17*), which provide altogether content values for 50 flavonoid aglycones. Several databases on isoflavone content in foods have also been developed (*34*). More recently, the Phenol-Explorer database was developed (*19*). Phenol-Explorer is the first comprehensive database on polyphenols in foods and includes information on content values in foods for 502 polyphenols mainly belonging to the following polyphenol classes: flavonoids, phenolic acids, lignans, and stilbenes. In particular, Phenol-Explorer is the first database on phenolic acids, widespread in foods, with over 100 compounds described. Phenol-Explorer contains information on glycosides and esters (**Table 2**), whereas the USDA database mainly contains data on aglycones. This distinction is important as glycosides and esters are often more abundant in foods than their corresponding aglycones (**Table 6**) and they also show different biological properties. This has been well described for bioavailability (*35*−*38*).

Phenol-Explorer also differs from the USDA databases in the mode of evaluation of the data. A detailed method for data evaluation was developed by USDA based on sampling, number of samples, sample handling, analytical method, and analytical control (*39*). This method was tested and finally simplified to develop Phenol-Explorer, notably to save time in order to compile a much larger amount of composition data. Several exclusion criteria related to sample, analysis, and expression of results were applied to each content value compiled in Phenol-Explorer. Only those data considered to be of acceptable quality were included in the database. No confidence code was determined. However, the number of original content data, the overall number of samples analyzed, and the number and identity of each literature source from which the data originate are made easily accessible on the Website (www.phenol-explorer.eu) (*19*). Altogether, they are key parameters to evaluate the quality and reliability of each mean content value. Much less confidence should be given to a content value derived from the analysis of a single sample in a single laboratory, as compared to a value derived from the analysis of 956 samples collected from 36 publications as for resveratrol.

Two more differences between the USDA databases and Phenol-Explorer can be underscored. Phenol-Explorer contains

only data from the scientific literature and excludes any data originating from other sources (e.g., food industry) in order to guarantee a full traceability of the original data and of the corresponding documentation on samples and methods of sampling and analysis. A last difference is that composition data were also aggregated separately for the different categories of analytical methods, whereas in the USDA databases, data obtained by chromatography (flavonoid glycosides and aglycone) were aggregated together with the data obtained by chromatography after hydrolysis (after calculation of the corresponding content of aglycones for the glycosides).

Various authors have ranked foods or beverages according to their content in specific polyphenols (*40*−*44*) or total polyphenols as assayed by the Folin or ORAC methods (*6*, *45*, *46*). Foods and beverages are ranked here for the first time on the basis of the content of individual polyphenols and for all classes or subclasses of polyphenols (**Table 7**). The richest sources for each type of polyphenols can easily be spotted. Details on the content of each individual polyphenol in these foods and each (sub)class can easily be obtained on the Phenol-Explorer Website (www.phenol-explorer.eu).

The Phenol-Explorer database has also several limitations due in part to the insufficient data for some polyphenols such as proanthocyanidins or to the lack of reliable methods of analysis for complex polyphenols such as thearubigins in tea. With no doubt food scientists will continue to generate such data and to develop new methods of analysis for polyphenols.

The Phenol-Explorer database does not allow one to retrieve information on more specific foods such as different cultivars of fruits or different coffee brews. This is due to the too limited number of composition data available in the literature, which does not allow one to compare with a sufficient degree of confidence the concentrations of the various polyphenols in these specific foods. However, various text reports available on the Phenol-Explorer Website provide detailed information on the main factors (varieties, processing, storage conditions, cooking, etc.), which may affect the content in the various polyphenols in the different foods together with key references.

In summary, Phenol-Explorer provides detailed information on the content of all known polyphenols in foods. It allows one to easily identify the richest food sources for a given polyphenol or the various sources of a given polyphenol. These data can be used to compare polyphenol content of a new food product to those of common foods or to calculate the amount of polyphenols consumed with a given meal or diet. The food industry should benefit from this database in the development of new products with optimized technical, gustatory, functional, and health properties as should epidemiologists in the further development of research on the health effects of dietary polyphenols. Phenol-Explorer will be further developed to include data on polyphenol metabolism as well as retention factors for processed and cooked foods. It will also have to be regularly updated to insert new food composition data as they are published.

ACKNOWLEDGMENT

The construction of Phenol-Explorer has been supported by Unilever, Danone, and Nestlé.

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Received for review January 12, 2010. Revised manuscript received March 4, 2010. Accepted March 8, 2010.