## QUERIES -AJCN049247q

**[AQ1]** The sentence "The mean […] across participants)" was edited to clarify what ± values denote at first use in the abstract. Please confirm or amend.

**[AQ2]** Should clinicaltrials.org be changed to clinicaltrials.gov?

**[AQ3]** Per journal style, "level" was changed to "amount" or "concentration" when applicable throughout the article. Please confirm or amend.

**[AQ4]** Journal style is to change M to mol/L; please check throughout.

**[AQ5]** For clarity, "atom%" was changed to "atom percent excess." Okay as done?

**[AQ6]** Should clinicaltrials.org be changed to clinicaltrials.gov?

**[AQ7]** Per journal style, aliquot must not be used as a verb. Please amend the 2 instances in Biological sample collection accordingly.

**[AQ8]** Please spell out RP in RP-HPLC, PTFE, and, if not part of the product name, DSC in Discovery DSC-18 SPE columns and delete the acronyms.

**[AQ9]** Please spell out MWCO and delete the acronym and provide the name of the manufacturer of Amicon Ultra 2 cartridges.

**[AQ10]** Please spell out PFP and delete the acronym in Kinetix PFP if possible.

**[AQ11]** Because "A" (as "0.1% formic acid (vol:vol) in water"?) was only used once in the article, "(A)" was deleted after "0.1% formic acid (vol:vol) in water." However, please add the definition of B (eg, 0.1% formic acid (vol: vol) in title page footnote 4.

**[AQ12]** Please clarify the unit(s) of measure in "−22.85 ± 0.68/mil."

**[AQ13]** Please provide the page range of the chapter cited in reference 8, and confirm "Edtion ed" is correct.

**[AQ14]** Unable to verify the publication details of references 23 and 43. Please confirm or amend article information. If a reference is deleted, please renumber each in-text citation and corresponding reference accordingly.

**[AQ15]** Per the main text, protacatechuic was changed to protocatechuic in the legends of Figures 3 and 4. Please confirm or amend.

**[AQ16]** The text "*(h)*xcretion rate labeled cyanidin-hequoted ere collected over 48hours as illustrated" was deleted after "Time of maximum rate of elimination" in Table 1. Please confirm or amend.

**[AQ17]** Table footnotes were edited for clarity, and general-statement footnotes were combined in footnote 1 of each table, per journal style. Please confirm all table footnotes preserve your original intent.

# Human metabolism and elimination of the anthocyanin, cyanidin-3-glucoside: a $^{13}$C-tracer study[1-3]

*Charles Czank, Aedín Cassidy, Qingzhi Zhang, Douglas J Morrison, Tom Preston, Paul A Kroon, Nigel P Botting, and Colin D Kay*

## ABSTRACT

**Background:** Evidence suggests that the consumption of anthocyanin-rich foods beneficially affects cardiovascular health; however, the absorption, distribution, metabolism, and elimination (ADME) of anthocyanin-rich foods are relatively unknown.

**Objective:** We investigated the ADME of a $^{13}$C$_5$-labeled anthocyanin in humans.

**Design:** Eight male participants consumed 500 mg isotopically labeled cyanidin-3-glucoside (6,8,10,3′,5′-$^{13}$C$_5$-C3G). Biological samples were collected over 48 h, and $^{13}$C and $^{13}$C-labeled metabolite concentrations were measured by using isotope-ratio mass spectrometry and liquid chromatography–tandem mass spectrometry.

[AQ1] **Results:** The mean ± SE percentage of $^{13}$C recovered in urine, breath, and feces was 43.9 ± 25.9% (range: 15.1–99.3% across participants). The relative bioavailability was 12.38 ± 1.38% (5.37 ± 0.67% excreted in urine and 6.91 ± 1.59% in breath). Maximum rates of $^{13}$C elimination were achieved 30 min after ingestion (32.53 ± 14.24 $\mu$g$^{13}$C/h), whereas $^{13}$C-labeled metabolites peaked (maximum serum concentration: 5.97 ± 2.14 $\mu$mol/L) at 10.25 ± 4.14 h. The half-life for $^{13}$C-labeled metabolites ranged between 12.44 ± 4.22 and 51.62 ± 22.55 h. $^{13}$C elimination was greatest between 0 and 1 h for urine (90.30 ± 15.28 $\mu$g/h), at 6 h for breath (132.87 ± 32.23 $\mu$g/h), and between 6 and 24 h for feces (557.28 ± 247.88 $\mu$g/h), whereas the highest concentrations of $^{13}$C-labeled metabolites were identified in urine (10.77 ± 4.52 $\mu$mol/L) and fecal samples (43.16 ± 18.00 $\mu$mol/L) collected between 6 and 24 h. Metabolites were identified as degradation products, phenolic, hippuric, phenylacetic, and phenylpropenoic acids.

**Conclusion:** Anthocyanins are more bioavailable than previously perceived, and their metabolites are present in the circulation for [AQ2] ≤48 h after ingestion. This trial was registered at clinicaltrials.org as NCT01106729. *Am J Clin Nutr* 2013;97:1–9.

## INTRODUCTION

Interest in dietary anthocyanins continues to increase as evidence of their vascular bioactivity emerges from epidemiologic, clinical (randomized controlled trials), and in vitro studies (1–5). However, over the past decade, there has been ongoing speculation regarding the absorption, distribution, metabolism, and elimination (ADME)[4] and mechanisms of action of anthocyanins (6–8). Currently available ADME data from human-intervention studies have suggested maximal serum concentrations of anthocyanins and anthocyanidin phase II conjugates are, on average, reached by 1.5 h at amounts of ∼100 nmol/L after [AQ3] doses of ≤500 mg anthocyanins (6, 9–13). These findings have [AQ4] led to the supposition that anthocyanins are considerably less bioavailable than other flavonoid subclasses. Thus, epidemiologic observations that suggested that anthocyanin consumption is associated with reduced cardiovascular disease risk (1, 14) appear ambiguous because the average consumption of anthocyanins in the diet has been reported to be relatively low (12 mg/d in the United States) (15). Either anthocyanins are extremely potent and, therefore, active at low serum concentrations (ie, low nanomolar concentrations) or their dietary occurrence or bioavailability has been underestimated.

Evidence based on in vitro gastric (16) and microbial fermentation studies (17, 18) suggested that, after ingestion, anthocyanins are likely to be broken down (either spontaneously or enzymatically) into phenolic degradation products, which are then further metabolized. Similar findings were observed in a berry-extract human-consumption study, although because the intervention contained a complex profile of dietary phenolics, the metabolites could not be traced back conclusively to the anthocyanins over other phenolics within the extract (19). Isotope-tracer studies are required to conclusively establish the extent to which anthocyanins are metabolized to phenolic acid derivatives and the relative contribution of these metabolites to the absorption, distribution, and elimination of ingested anthocyanins.
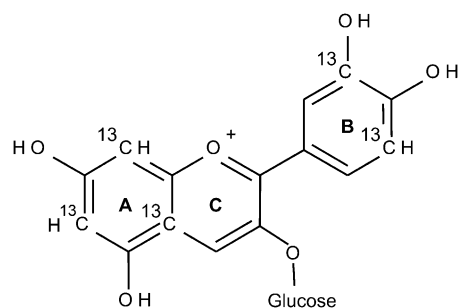
**FIGURE 1.** Structure and labeling configuration of 6,8,10,3′,5′-$^{13}C_5$-cyanidin-3-glucoside.

The aim of the current study was to trace metabolites derived from both phenolic rings (**Figure 1**, A and B rings) of the parent-anthocyanin structure, to establish a complete profile of their absorption and elimination kinetics. To our knowledge, this is the first study to feed a chemically synthesized multistable-isotope labeled anthocyanin [cyanidin-3-glucoside (C3G)] to establish bioavailability and identify metabolites in humans.

## SUBJECTS AND METHODS

### Isotopically labeled anthocyanin tracer

Isotopically labeled C3G that contained three $^{13}C$ atoms on the A ring and 2 $^{13}C$ atoms on the B ring [6,8,10,3′,5′-$^{13}C_5$-C3G ($^{13}C_5$-C3G); Figure 1] was synthesized as previously described [AQ5] (20)(with an enrichment of 99 atom% atom percent excess at each position and established as 99.8% pure $^{13}C_5$-C3G by using HPLC–tandem mass spectrometry (HPLC-MS/MS) and was accurately weighed and encapsulated (250-mg gelatin capsules) at the Ipswich Hospital Pharmaceutical Manufacturing unit.

### Subjects

A classic single-bolus oral pharmacokinetic study design was carried out in 8 healthy male participants recruited from the University of East Anglia and local community of Norwich, United Kingdom. The healthy participants were chosen to maintain a homogeneous study population and minimize metabolic variation. Participants were nonsmokers, had BMI (kg/m$^2$) in the range from 18.5 to 30.5, and were aged 18–45 y, moderate drinkers, and not taking dietary supplements. The protocol was explained to participants, and they provided informed consent. The study was conducted at the Clinical Research and Trials

Unit at the University of East Anglia according to the principles expressed in the Declaration of Helsinki and was approved by the local Research Ethics Committee (ref 10/H0306/42) and registered at clinicaltrials.org as NCT01106729.          [AQ6]
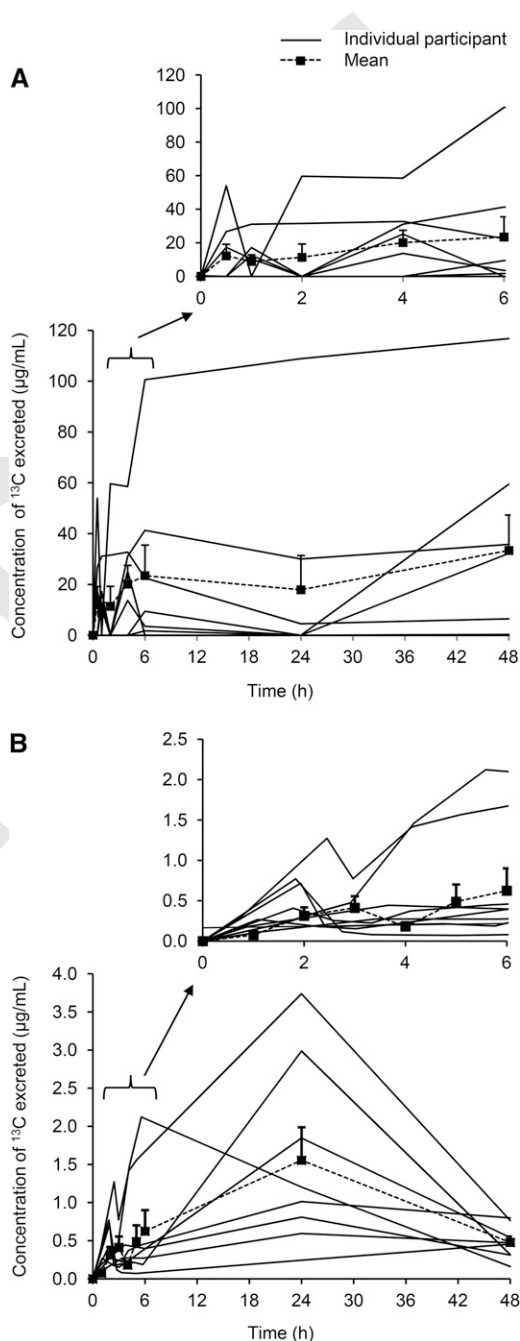


**FIGURE 2.** Individual concentrations of $^{13}C$ tracer in whole blood (A) and urine (B) across participants after the consumption of a 500-mg bolus dose of $^{13}C_5$-cyanidin-3-glucoside by healthy male participants over 48 h and expanded views of first 6 h (insets). Dashed lines represents means ± SEs ($n = 8$). For whole blood (A), the dashed line represents the mean (±SE) for 8 participants ($n = 8$); however, several data points are obscured by the $x$-axis where the $^{13}C$ content was below detection limits. For urine (B), the dashed line represents the mean (±SE) number of participants who provided a sample in a given period of time: $t = 0$–1 h ($n = 3$), $t = 1$–2 h ($n = 6$), $t = 2$–3 h ($n = 6$), $t = 3$–4 h ($n = 6$), $t = 4$–5 h ($n = 4$), $t = 5$–6 h ($n = 8$), $t = 6$–24 h ($n = 8$), and $t = 24$–48 h ($n = 8$).

**TABLE 1**
Rates of elimination and time of peak elimination observed for the $^{13}C$ tracer in 8 healthy adult males after consumption of 500 mg $^{13}C_5$-C3G[1]

| [AQ16] Sample | Maximum rate of elimination | Time of maximum rate of elimination |
|---|---|---|
| | $\mu g/h$ | $h$ |
| Blood | 32.53 ± 14.24 | 0.5 |
| Urine | 90.30 ± 15.28 | 0–1 |
| Breath | 132.87 ± 32.23 | 6 |
| Feces | 557.28 ± 247.88 | 6–24 |

[AQ17]     [1] Concentration of $^{13}C$ was quantified by using liquid chromatography–isotope-ratio mass spectrometry (mean ± SE; $n = 8$). C3G, cyanidin-3-glucoside.

## Study design

After fasting overnight, participants provided blood (30 min and 1, 2, 4, 6, 24, and 48 h), urine (individual voids between 0 and 6 h; total voids between 6 and 24 and 24 and 48 h), breath (30 min and 1, 2, 4, 6, 24, 48 h), and fecal (all voids between 0 and 6, 6 and 24, and 24 and 48 h) samples after the consumption of a 500-mg (as two 250-mg capsules) single oral bolus dose of $^{13}C_5$-C3G (*see* Figure 1 under "Supplemental data" in the online issue). A standardized breakfast was provided 30 min postbolus and a standardized lunch between the 2- and 4-h sample-collection time points. Standardized breakfasts were also provided on each of the follow-up days (for 24 and 48 h).

## Dietary intake

Participants were asked to avoid anthocyanin-rich foods and foods that contained a higher natural abundance of $^{13}C$ (21) over the 7-d period (washout period) before the administration of the capsule and during the intervention (a list of foods to avoid was provided). Completed food diaries during the washout period (3 d), study day, and 4-h follow-up were monitored for compliance. Macronutrient and micronutrient intakes were calculated with the WISP software package (version 3; Tinuviel Software), and polyphenol intake was determined with the Phenol Explorer V2.0 database (http://www.phenol-explorer.eu) (22).

## Biological sample collection

Blood was collected via a cannula for the first 6 h and via venepuncture at 24 and 48 h into untreated 10-mL evacuated tubes. For isotope-ratio mass-spectrometry (IRMS) analysis, [AQ7] whole blood samples were aliquoted into cryovials (Sigma Aldrich) and frozen immediately in liquid nitrogen, whereas for the HPLC-MS/MS analysis, blood samples were allowed to clot for 1 h followed by centrifugation at $3000 \times g$ for 10 min. The serum was acidified to pH 2.4 with formic acid by using a pH meter (Omega) to prevent degradation of anthocyanins (16) and aliquoted into cryovials for storage. Breath samples were collected simultaneously (with blood samples) by using the Alveosampler system (QuinTrony) and stored in 10-mL evacuated tubes at room temperature for IRMS. Individual and complete urine voids were collected into Urisafe collection containers

(VWR International) with 100 mg ascorbate added per 500 mL urine and were acidified manually to pH 2.4 with formic acid. Individual fecal voids were collected into custom-made stool-collection kits, weighed, and transferred to ultracold storage containers (Nalgene). All blood, serum, urine, and feces samples were stored at $-80°C$ until analysis.

## Analytic methods

### Chemicals and materials

C3G was obtained from Extrasynthese, whereas phase II conjugates of phenolic acids [protocatechuic acid (PCA)–3-glucuronide, PCA-4-glucuronide, vanillic acid-4-glucuronide, benzoic acid-4-glucuronide, isovanillic acid-3-glucuronide, isovanillic acid-3-sulfate, PCA-4-sulfate, vanillic acid-4-sulfate, PCA-3-sulfate, and benzoic acid-4-sulfate] were synthesized as previously described (23). HPLC-MS/MS–grade methanol and acetonitrile were purchased from Fisher Scientific. Strata-X solid-phase extraction (SPE) columns (6 mL, 500 mg), a Kinetex polyfluorophenol RP-HPLC column (2.6 $\mu$m; 100 $\times$ 4.6 [AQ8] mm), and SecurityGuard cartridges (polyfluorophenol; 4 $\times$ 2.0 mm) were purchased from Phenomenex. Bond Elute C18 (20 mL; 5 g) SPE columns were purchased from Agilent. Discovery DSC-18 SPE columns (6 mL; 1 g) and Acrodisc 13-mm, 0.45-$\mu$m PTFE syringe filters and all other chemicals were purchased from Sigma-Aldrich.

### IRMS

A total of 0.5 mL whole blood (diluted 1:1 with 0.5 mL 4 M NaCl) or 1 mL urine samples was transferred to ultrafiltration cartridges (Amicon Ultra 2; 30,000 MWCO) and centrifuged at [AQ9] $6000 \times g$ for 20 min. Ultrafiltered blood and urine were subsequently analyzed by using liquid chromatography-IRMS (IsoPrime) via a direct-injection mode by using previously described methods (24, 25). Breath samples were analyzed by using continuous-flow IRMS (AP 2003; IsoPrime). Aliquots (4 mg) of each fecal sample were weighed into tin capsules, which yielded $\sim 400$ $\mu$g carbon for elemental analysis IRMS (Sercon). In each IRMS analysis, the $CO_2$ generated was calibrated against Vienna Pee Dee Belemnite by using calibrated laboratory standards as previously described (26).

**TABLE 2**
Pharmacokinetic characteristics of metabolites in serum over 48 h in 8 healthy adult males after consumption of 500 mg $^{13}C_5$-C3G[1]

| Metabolites | $C_{max}$ | $t_{max}$ | $AUC_{0–48}$ | $t_{1/2}$ |
|---|---|---|---|---|
| | $\mu mol/L$ | $h$ | $\mu mol \cdot h/L$ | $h$ |
| C3G | $0.14 \pm 0.05$ | $1.81 \pm 0.16$ | $0.31 \pm 0.13$ | ND |
| Degradants | $0.72 \pm 0.23$ | $6.06 \pm 0.75$ | $9.09 \pm 3.01$ | $12.44 \pm 4.22$ |
| Phase II conjugates of PCA | $2.35 \pm 0.15$ | $13.44 \pm 2.46$ | $43.92 \pm 5.05$ | $29.52 \pm 8.95$ |
| Ferulic acid | $0.94 \pm 0.37$ | $11.29 \pm 4.23$ | $21.22 \pm 10.99$ | $51.62 \pm 22.55$ |
| Hippuric acid | $1.96 \pm 1.39$ | $15.69 \pm 4.07$ | $46.42 \pm 30.31$ | $21.69 \pm 4.56$ |

[1] All values are means $\pm$ SEs. Serum concentrations of metabolites were quantified by using HPLC–tandem mass spectrometry ($n = 8$). $AUC_{0–48}$, AUC (0–48 h); C3G, cyanidin-3-glucoside; $C_{max}$, maximum serum concentration; degradants, sum of protocatechuic acid and phloroglucinaldehyde; ND, analyte identified in too few time points to model pharmacokinetics ($\leq 3$); PCA, protocatechuic acid; phase II conjugates of PCA, sum of phase II conjugates of PCA (including PCA-3-glucuronide, PCA-4-glucuronide, PCA-3-sulfate, PCA-4-sulfate, vanillic acid, isovanillic acid, vanillic acid-glucuronide, isovanillic acid-glucuronide, vanillic acid-sulfate, isovanillic acid-sulfate, methyl 3,4-dihydroxybenzoate, and 2-hydroxy-4-methoxybenzoic acid); $t_{max}$, time to reach maximum serum concentration; $t_{1/2}$, elimination half-life.
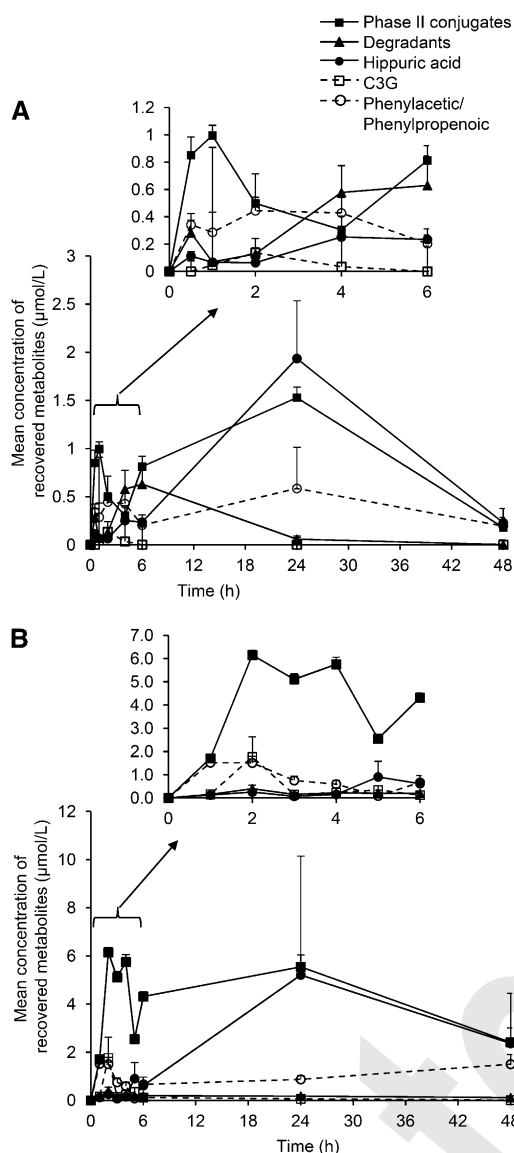
**FIGURE 3.** Mean (±SE) concentrations of identified metabolites in serum (A) and urine (B) after the consumption of a 500-mg bolus dose of $^{13}C_5$-C3G by 8 healthy male participants over 48 h and expanded views of the first 6 h (insets). C3G, cyanidin-3-glucoside; Degradants, sum of [AQ15] protocatechuic acid and phloroglucinaldehyde; PCA, protocatechuic acid; phase II conjugates, sum of phase II conjugates of PCA (including PCA-3-glucuronide, PCA-4-glucuronide, PCA-3-sulfate, PCA-4-sulfate, vanillic acid, isovanillic acid, vanillic acid-glucuronide, isovanillic acid-glucuronide, vanillic acid-sulfate, isovanillic acid-sulfate, methyl 3,4-dihydroxybenzoate, and 2-hydroxy-4-methoxybenzoic acid); Phenylacetic/Phenylpropenoic, sum of ferulic acid, 3,4-dihydroxyphenylacetic acid, and 4-hydroxyphenylacetic acid.

### HPLC-MS/MS

Serum, urine, and fecal samples were extracted by SPE with and extraction efficiencies of 84.5 ± 15.9% for serum, 84.0 ± 9.5% for urine, and 78.8 ± 1.3% for feces. Fecal samples were homogenized, freeze dried, and alcohol extracted (50% methanol in phosphate-buffered saline; pH 2.4) before SPE. Sample [AQ10] extracts (5 μL) were injected onto a Kinetix PFP column (Phenomonex) and separated with an Agilent 1200 HPLC by [AQ11] using 0.1% formic acid (vol:vol) in water and 0.1% formic acid (vol:vol) in acetonitrile (B) at a flow rate of 1.5 mL/min and

gradient that consisted of 1% B at 0 min and was ramped to 30% B over 32.5 min. Metabolite identification was performed by using a QTrap 4000 linear ion-trap mass spectrometer (AB-Sciex) by using multireaction monitoring optimized for the detection of pure standards with a *m/z* of the parent and daughter fragments adjusted to +2 or +3 *m/z* units, which allowed for the identification of $^{13}C$-labeled metabolites. Metabolites were confirmed on the basis of the retention time and ≥3 parent-daughter ion-fragmentation transitions.

### Data processing and statistical analysis

IRMS data were collected and expressed as $\delta^{13}C$ (relative to Vienna Pee Dee Belemnite) and, where appropriate, converted to parts per million $^{13}C$. Absolute tracer excretion in the breath was calculated by estimating the $CO_2$ production rate (27) from the body surface area (28) by using an estimated correction of physical activity levels (of 1.3) appropriate for sedentary behavior (26). Absolute tracer excretion was determined in urine and feces as the product of the total amount of carbon excreted calculated from the area ratio of the major ion beam (*m/z* 44) of the sample compared with the laboratory standard of known carbon content and the $^{13}C$ enrichment of the sample. The amount of the tracer excreted in each pool was calculated by summation of the tracer excreted in the study period and expressed as percentage of the administered dose of $^{13}C$. A similar calculation was undertaken for blood to determine the instantaneous percentage of the dose transiting the serum pool.

HPLC-MS/MS data were collected with Analyst 1.5.1 software (ABSciex, California), and the peak-area data for the most abundant ion-pair transition for each compound was exported to the Excel 2007 program (Microsoft). The peak area of $^{13}C$ metabolites was quantified against the slope of the fitted regression line of pure standards (which had been subtracted for the baseline ionization signal to account for differences in background ionization between $^{13}C$ and $^{12}C$ compounds). Data from all individual urine samples were pooled to the nearest 1-h period during the first 6 h. Fecal concentrations wee expressed relative to 1 g wet weight. The proportion of $^{13}C$-labeled metabolites relative to total $^{13}C$ was established by calculating the fractional molar contribution of $^{13}C$ atoms in the metabolites and the total $^{13}C$ concentration (μmol $^{13}C$/L)by using the volume for the urine and fecal water content. Pharmacokinetic modeling of metabolite concentrations was performed with the program PKSolver (29) for Excel 2007 (Microsoft) by using noncompartmental analysis. All values are presented as means ± SEs (*n* = 8) unless otherwise stated.

### RESULTS

### Study participants

Eight male participants, with a mean age of 27.8 ± 8.1 y and BMI of 23.2 ± 1.5, completed the study. Anthocyanin consumption (mean ± SD) during the washout period was 3.3 ± 3.5 mg/d (*see* Table 1 under "Supplemental data" in the online issue for mean baseline characteristics) and intake was <0.5 mg on the study day and follow-up days. The mean basal breath $CO_2$ natural abundance of $\delta^{13}C$ was −22.85 ± 0.68/mil, which in- [AQ12] dicated a low natural abundance $^{13}C$ had been achieved across

participants. Therefore, all participants complied with the study protocol, and no adverse effects were associated with the single dose of $^{13}C_5$-C3G.

## Elimination of $^{13}C$

The maximal rate of $^{13}C$ elimination (32.53 ± 14.24 $\mu$g/h) was observed at 30 min after ingestion (**Table 1**), with blood concentrations of $^{13}C$ that ranged between 8.91 ± 3.99 and 23.47 ± 12.05 $\mu$g/mL over the first 24 h (**Figure 2**A), and peak concentrations were reached at 48 h (33.40 ± 13.90 $\mu$g/mL). The sum of all $^{13}C$-labeled metabolites reached a total peak concentration of 5.97 ± 2.14 $\mu$mol/L in serum at 10.25 ± 4.14 h on the basis of pharmacokinetic modeling (**Table 2**; **Figure 3**A). The half-life of $^{13}C$-labeled metabolites ranged from 12.44 ± 4.22 h for degradation products (PCA and phloroglucinaldehyde) to ≤51.62 ± 22.55 h for ferulic acid (Table 2).

Maximum elimination rates for $^{13}C$ (Table 1) in urine (90.30 ± 15.28 $\mu$g/h) occurred between 0 and 1 h after ingestion (Figure 2B), in breath occurred at 6 h (132.87 ± 32.23 $\mu$g/h) and in feces occurred between 6 and 24 h (557.28 ± 247.88 $\mu$g/ h). The highest concentration of $^{13}C$ was observed in urine (1.55 ± 0.43 $\mu$g/mL) during the 6–24 h (Figure 2B) time period postingestion, in breath (2341.62 ± 1010.22 $\mu$g/mL) at 24 h, and in feces (105.69 ± 20.68 $\mu$g/g) at 24–48 h (**Figure 4**A). In relation to metabolites (sum of all degradants and their metabolites), greatest concentrations were shown in 6–24-h urine samples (10.77 ± 4.52 $\mu$mol/L; Figure 3B) and 6–24-h fecal samples (43.16 ± 18.00 $\mu$mol/L; Figure 4B).

Urine was the primary route of elimination over the first 6 h (**Figure 5**A) and represented 66.33 ± 13.22% of the total $^{13}C$ recovery followed by that in breath (28.94 ± 6.89%). Feces represented the major route of elimination over the 6–24- and 24–48-h time periods (Figure 5A). A similar pattern was observed for metabolites, with highest concentrations of $^{13}C$-labeled metabolites in urine in the first 6 h (5.57 ± 2.56 $\mu$mol/L;

Figure 5B), whereas feces was the predominant compartment thereafter (Figure 5B).

A total of 43.9 ± 25.9% of the bolus dose of $^{13}C$ was recovered in urine, breath, and feces, with a wide interindividual variability (15.1–99.3%) exhibited by participants. Maximum observed quantities of $^{13}C$ in blood accounted for 0.18 ± 0.11% of the ingested dose, whereas mean recoveries of $^{13}C$ were 5.37 ± 0.67%, 6.91 ± 1.59%, and 32.13 ± 6.13% for urine, breath, and feces, respectively (Figure 5A). Together, these data suggest a relative bioavailability of ≥12.38 ± 1.38% calculated from the combined elimination via urine and breath.

## Characteristics of $^{13}C$-labeled metabolites

A total of 25 $^{13}C$-labeled compounds that consisted of $^{13}C_5$-C3G and 24 labeled metabolites were identified. Metabolites included phase II conjugates of C3G and cyanidin (cyanidin-glucuronide, methyl cyanidin-glucuronide, and methyl C3G-glucuronide), degradants (PCA, phloroglucinaldehyde, and phloroglucinaldehyde), phase II conjugates of PCA (including PCA-3-glucuronide, PCA-4-glucuronide, PCA-3-sulfate, PCA-4-sulfate, vanillic acid, isovanillic acid, vanillic acid-glucuronide, isovanillic acid-glucuronide, vanillic acid-sulfate, isovanillic acid-sulfate, methyl 3,4-dihydroxybenzoate, 2-hydroxy-4-methoxybenzoic acid, and methyl vanillate), phenylacetic acids (3,4-dihydroxyphenyl acetic acid and 4-hydroxyphenylacetic acid), phenylpropenoic acids (caffeic acid and ferulic acid), and hippuric acid.

In serum, C3G reached a peak concentration of 0.14 ± 0.05 $\mu$mol/L at 1.81 ± 0.16 h postconsumption, whereas its degradation products peaked at 0.72 ± 0.23 $\mu$mol/L (Table 2). The major metabolites of C3G in serum were phase II conjugates of PCA, ferulic acid, and hippuric acid, which peaked between 6- and 24-h collection time points at concentrations between 0.94 ± 0.37 and 2.35 ± 0.15 $\mu$mol/L. The serum concentration AUC ranged from 0.31 ± 0.13 $\mu$mol · h/L for C3G to 46.42 ± 30.31 $\mu$mol · h/L (Table 2) for hippuric acid.
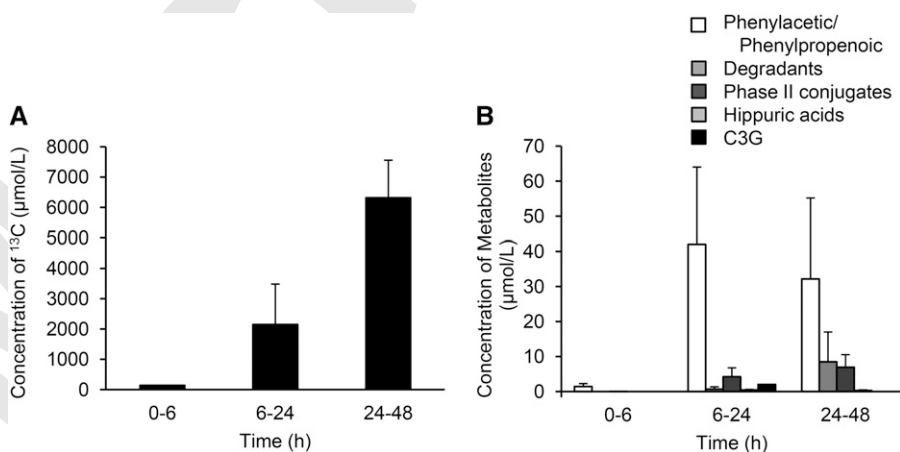


**FIGURE 4.** Mean (±SE) concentrations of $^{13}C$ tracer (A) and $^{13}C$-labeled metabolites (B) in feces after the consumption of a 500-mg bolus dose of $^{13}C_5$-C3G by 8 healthy male participants. Eight participant samples were collected for the 6–24- and 24–48-h time points, whereas 2 participants provided samples within the first 6 h of sampling. C3G, cyanidin-3-glucoside; Degradants, sum of PCA and phloroglucinaldehyde; PCA, protocatechuic acid; phase II conjugates, sum of phase II conjugates ofPCA (including PCA-3-glucuronide, PCA-4-glucuronide, PCA-3-sulfate, PCA-4-sulfate, vanillic acid, isovanillic acid, vanillic acid-glucuronide, isovanillic acid-glucuronide, vanillic acid-sulfate, isovanillic acid-sulfate, methyl 3,4-dihydroxybenzoate, 2-hydroxy-4-methoxybenzoic acid, and methyl vanillate); Phenylacetic/Phenylpropenoic, sum of ferulic acid, caffeic acid, and 3,4-dihydroxyphenylacetic acid, and 4-hydroxyphenylacetic acid.
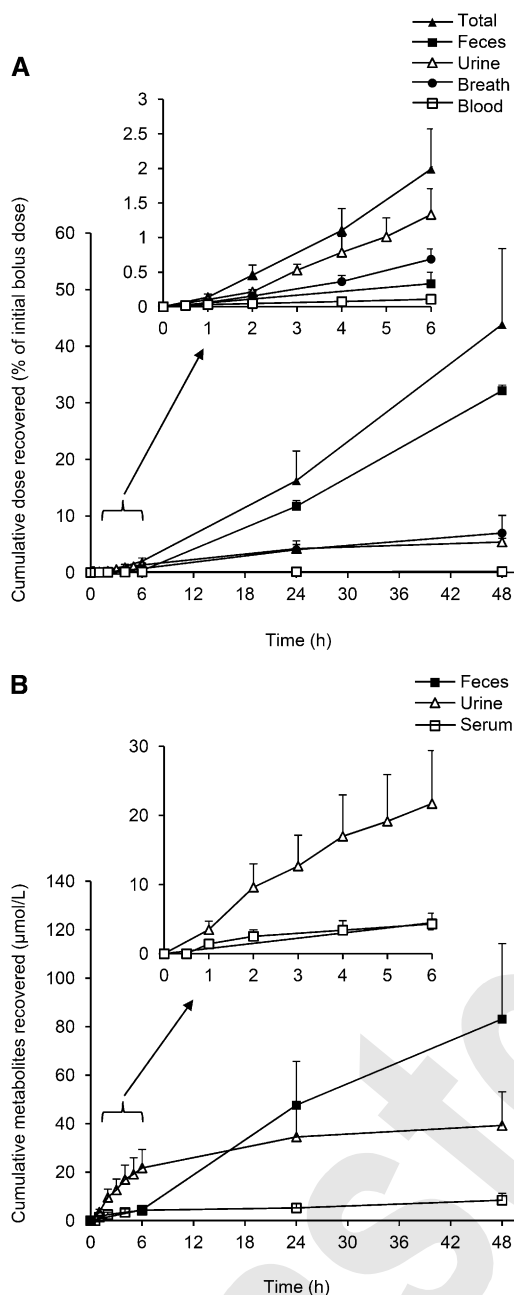
**FIGURE 5.** Cumulative recovery ($\pm$SE) of $^{13}$C from whole blood (A) and $^{13}$C-labeled metabolites from blood serum (B) after the consumption of a 500-mg bolus dose of $^{13}$C$_5$-cyanidin-3-glucoside by 8 healthy male participants over 48 h and expanded views of first 6 h (insets).

C3G and its degradants reached a peak in urine at 2 h post-consumption (**Table 3**) at $1.78 \pm 0.18$ and $0.48 \pm 0.10$ $\mu$mol/L, respectively (Figure 3B). Also, phase II conjugates of C3G and cyanidin were identified in the urine at a maximum concentration of $1.17 \pm 0.52$ $\mu$mol/L at 1 h (collectively) and consisted of cyanidin-glucuronide (*m/z* 468/454/292), methylated cyanidin-glucuronide (*m/z* 482/468/292), and methylated C3G-glucuronide (*m/z* 644/482/468/292) on the basis of tandem mass spectrometry fragmentation patterns and quantified relative to C3G (because analytic standards were not available). Phase II conjugates of PCA peaked in the urine at 24 h ($5.54 \pm 0.49$ $\mu$mol/L), phenylacetic and phenylpropenoic acids at 48 h ($1.51$

$\pm$ 0.75 $\mu$mol/L), and hippuric acid at 24 h ($5.21 \pm 3.43$ $\mu$mol/L). Out of the total $^{13}$C recovered in the urine (by using IRMS), $36.72 \pm 14.39\%$ could be accounted for as $^{13}$C-labeled metabolites (by using HPLC-MS/MS), with the specific urinary recovery of metabolites that ranged from $36.47 \pm 20.27$ ng for C3G to $1124.89 \pm 830.70$ ng for phase II conjugates of PCA (**Table 4**).

Total metabolites present in feces reached a maximal concentration at 24 h postconsumption ($43.16 \pm 18.32$ $\mu$mol/L) with phase II conjugates of PCA that reached peak concentrations of $6.94 \pm 3.59$ $\mu$mol at 48 h, whereas the majority of fecal metabolites were comprised of phenylpropenoic and phenylacetic acids ($41.69 \pm 11.55$ $\mu$mol/L) that peaked at 6–24 h (Figure 4B). The hippuric acid content of feces reached a peak of $0.42 \pm 0.17$ $\mu$mol/L at 24 h (Figure 4B). Out of the total $^{13}$C recovered in feces (by IRMS), $2.01 \pm 0.01\%$ could be accounted for as $^{13}$C-labeled phenolic metabolites (by using HPLC-MS/MS), with the specific fecal recovery of metabolites that ranged from 0.44 ng for C3G to $56.00 \pm 34.64$ ng for phenylacetic and propenoic acids (Table 4).

## DISCUSSION

C3G was established to have a minimum relative bioavailability of $12.38 \pm 1.38\%$ on the basis of the total elimination of the absorbed $^{13}$C dose via urine and breath. In samples collected, a maximum of $0.18 \pm 0.11\%$ of the $^{13}$C dose could be recovered from blood, $5.37 \pm 0.67\%$ of the $^{13}$C dose could be recovered from urine, $6.91 \pm 1.59\%$ of the $^{13}$C dose could be recovered from breath, and $32.13 \pm 6.13\%$ of the $^{13}$C dose could be recovered from feces. Previously, anthocyanins have been reported to have one of the lowest bioavailabilities of all of the dietary flavonoid subclasses ($\sim$0.4%) (7, 30). However, our data suggested that anthocyanins are as bioavailable as other flavonoid subclasses, such as flavan-3-ols and flavones, which have relative bioavailabilities between 2.5% and 18.5% (7, 30). There was also considerable interindividual variability in the recovery of the $^{13}$C tracer in the current study that ranged from 15.1% to 99.3%, probably as a result of a high variation in gastric and intestinal transit times, composition, and catabolic activity of colonic flora and the ability to take up and excrete catabolites and metabolites (6).

A total of $43.9 \pm 25.9\%$ of the dose of $^{13}$C was recovered in urine, breath, and feces; however the fate of the remaining ingested $^{13}$C remains unknown. The recovery of flavonoids similar in structure to C3G (such as $^{14}$C-labeled quercetin) has been reported to be between 58.5% and 96% (31, 32). Furthermore, of the total $^{13}$C recovered, only $36.72 \pm 14.39\%$ and $2.01 \pm 0.01\%$ of the tracer was recovered as $^{13}$C-labeled metabolites in the urine and feces respectively, which suggested that there are many metabolites still undetected by current HPLC-MS/MS techniques. On the basis of the instability of anthocyanins and appearance of a relatively large number of diverse breakdown products and metabolites, other metabolites might exist at lower concentrations and, therefore, escape detection.

Serum concentrations of C3G that we observed were similar to those previously reported (6, 7); however, degradation products of C3G (PCA and phloroglucinaldehyde) reached collective peak serum concentrations of $0.72 \pm 0.23$ $\mu$mol/L (Table 2) at $6.06 \pm 0.75$ h postbolus, which, to our knowledge, has not been

**TABLE 3**

Peak concentrations of urinary metabolites over 48 h in 8 healthy adult males after consumption of 500 mg $^{13}C_5$-C3G[1]

| Metabolites | Maximum concentration[2] | Time of maximum concentration |
|---|---|---|
| | *μmol/L* | *h* |
| C3G | 1.78 ± 0.18 | 2 |
| Phase II conjugates of C3G and cyanidin | 1.17 ± 0.52 | 1 |
| Degradants | 0.48 ± 0.10 | 2 |
| Phase II conjugates of PCA | 5.54 ± 0.49 | 24 |
| Phenylpropenoic and phenylacetic acids | 1.51 ± 0.75 | 48 |
| Hippuric acid | 5.21 ± 3.43 | 24 |

[1] Urinary concentrations of metabolites quantified by using HPLC–tandem mass spectrometry (*n* = 8). C3G, cyanidin-3-glucoside; degradants, sum of protocatechuic acid and phloroglucinaldehyde; PCA, protocatechuic acid; phase II conjugates of C3G and cyanidin, sum of cyanidin-glucuronide, methylated cyanidin-glucuronide, and methylated C3G-glucuronide; phase II conjugates of PCA, sum of phase II conjugates of PCA (including PCA-3-glucuronide, PCA-4-glucuronide, PCA-3-sulfate, PCA-4-sulfate, vanillic acid, isovanillic acid, vanillic acid-glucuronide, isovanillic acid-glucuronide, vanillic acid-sulfate, isovanillic acid-sulfate, methyl 3,4-dihydroxybenzoate, and 2-hydroxy-4-methoxybenzoic acid); phenylpropenoic and phenylacetic acids, sum of ferulic acid, 3,4-dihydroxyphenylacetic acid, and 4-hydroxyphenylacetic acid.
[2] All values are means ± SEs.

previously reported. On the basis of the rapid appearance of C3G degradation products and their phase II conjugates within the serum, some degradation likely occurred in the small intestine (either preabsorption or postabsorption), which suggested that anthocyanin C-ring cleavage may not require the action of colonic microflora as reported for other flavonoids such as quercetin and catechin (18).

A total of 24 metabolites were identified at concentrations that ranged from 0.1 to 42.2 *μ*mol/L, whereas a total of 51 putative metabolites of C3G were initially explored. Seven hydroxybenzoic acids, 10 methoxybenzoic acids, 3 phenylpropenoic acids, 2 isomers of methylhippuric acid, homovanillic acid, hydroxybenzylalcohol, benzoic acid-4-sulfate, and hydroxybenzaldehydes were either not present or only present in trace amounts. Although many of the metabolites identified in the current study have been identified in animal studies (18, 33, 34), to our knowledge, this is the first study to show this diversity of metabolites in humans by using a stable-isotope–labeled single-compound approach.

Estimates of the half-lives of elimination were between 12.44 ± 4.22 h and 51.62 ± 22.55 h for $^{13}$C-labeled metabolites (Table 2), which suggested a relatively slow urinary clearance of some metabolites. Long elimination half-lives may be the result of a combination of hepatic recycling, enterohepatic circulation, and prolonged colonic production and absorption. Indeed, the biliary excretion of C3G (35) and other similarly structured flavonoids (quercetin and catechin) (31, 32, 36, 37) has previously been reported in animal studies.

The urinary recovery of $^{13}$C reached a maximal concentration in the pooled 6–24-h collections, which represented a peak $^{13}$C-labeled metabolite concentration of 10.77 ± 4.52 *μ*mol/L (Figure 3B). These concentrations were considerably higher than those previously published (0.02–0.592 *μ*mol/L) (6, 7). In the breath, peak concentrations of the $^{13}$C tracer were detected at 24 h as $^{13}CO_2$ (Figure 5). To our knowledge, this is the first human study to report the breath as a route for the clearance of anthocyanin-derived carbon from the body. The sustained excretion of the label as $^{13}CO_2$ over 48 h suggested the prolonged absorption of low molecular weight fecal metabolites from the

**TABLE 4**

Recovery of metabolites in biological samples over 48 h in 8 healthy adult males after consumption of 500 mg $^{13}C_5$-C3G[1]

| Metabolites | Serum[2] | Urine[3] | Feces[3] |
|---|---|---|---|
| | *ng* | *ng* | *ng* |
| C3G | 9.99 ± 3.90 | 36.47 ± 20.27 | 0.44[4] |
| Degradants | 149.88 ± 93.20 | 60.00 ± 23.24 | 7.40 ± 1.81 |
| Phase II conjugates of PCA | 321.73 ± 130.89 | 1124.89 ± 830.70 | 30.82 ± 11.39 |
| Phenylacetic/propenoic acids | 153.32 ± 60.95[5] | 248.59 ± 85.28 | 56.00 ± 34.64 |
| Hippuric acid | 348.04 ± 246.32 | 309.82 ± 261.92 | 4.26 ± 2.29 |

[1] All values are means ± SEs. Metabolite recovery determined by using HPLC–tandem mass spectrometry (*n* = 8). C3G, cyanidin-3-glucoside; degradants, sum of protocatechuic acid and phloroglucinaldehyde; PCA, protocatechuic acid; phase II conjugates of PCA, sum of phase II conjugates of PCA (including PCA-3-glucuronide, PCA-4-glucuronide, PCA-3-sulfate, PCA-4-sulfate, vanillic acid, isovanillic acid, vanillic acid-glucuronide, isovanillic acid-glucuronide, vanillic acid-sulfate, isovanillic acid-sulfate, methyl 3,4-dihydroxybenzoate, 2-hydroxy-4-methoxybenzoic acid, and methyl vanillate).
[2] Recovery at maximum serum concentration.
[3] Total recovery.
[4] C3G was detected in feces of one participant only.
[5] Ferulic acid was the only phenylacetic/propenoic acid recovered in serum.

colon, perhaps derived from labeled-aliphatic compounds or carboxylic acids or via direct fermentation to $^{13}CO_2$. Studies in which $^{14}C$-labeled flavonoids were fed to rodents reported between 8% and 17.5% excretion as $^{14}CO_2$ (35, 38), in addition to the presence of $^{14}C$-labeled aliphatic intermediates (41). The greatest proportion of the $^{13}C$ dose was excreted in feces (32.13 ± 6.13%). A previous study reported 44.5% recovery of an oral bolus dose of $^{14}C$-labeled C3G in mice (35,) and fecal recoveries of other flavonoids have been reported between 1.9% and 30% (33, 34).

In the current study, there was a 42-fold higher abundance of $^{13}C$-labeled metabolites relative to $^{13}C_5$-C3G at their respective maximum serum concentration. Previous studies reported a 6-fold higher proportion of $^{14}C$ metabolites relative to the parent anthocyanin in mice fed $^{14}C$-labeled C3G (35). Phase II conjugates of C3G could only be detected in the urine and reached peak concentrations of 1.17 ± 0.52 $\mu$mol/L at 1 h (collectively). Previous studies in which similarly structured isotope-labeled flavonoids (quercetin and catechin) were fed have also reported glucuronide, methyl, or sulfate derivatives of the parent flavonoid structure (36–38). Phase II metabolites of PCA were the primary metabolites identified during the first 6 h in serum and urine (Figure 3), whereas hippuric, phenylacetic, and phenylpropenoic acids and phase II conjugates of PCA were the predominant metabolites at 24 h in serum. In the 48-h samples, a mixture of hippuric acid, ferulic acid, and phase II conjugates of PCA were present (Figure 3).

Although the study was limited to men only, there was a high variation in ADME observed, which suggested an extremely high variability in ADME should be expected across mixed-sex populations as a result of differences in absorption, metabolism, and, perhaps more importantly, the gut microbiome (18); all of which should be considered when associations in epidemiologic studies on the health effects of flavonoid consumption are interpreted.

A limitation of the current study was the inability to recover all of $^{13}C$ label or $^{13}C$-labeled metabolites, for which there were many possible reasons. Primarily, a considerable proportion of the unrecovered label likely remained in feces >48 h because concentrations of $^{13}C$ did not reach their peak by this time (Figure 5A), which suggested that a longer fecal sampling period (perhaps ≥72 h) would have yielded a greater recovery. Extraction and quantification methods used were also optimized for 51 analytes, and therefore, the methods may be less sensitive in the detection or quantification of other novel metabolites. Furthermore, extraction efficiencies of the methods used were 75–98% efficient across matrices, which potentially accounted for ≤25% of identified metabolites having been quantitatively underestimated. Although we did not fully recover the $^{13}C$ dose (via IRMS) or the relative concentration of $^{13}C$-labeled metabolites (via HPLC-MS/MS), the current results improved on those of previous studies in which the recovery of metabolites rarely exceeded 1% of the dose (7, 10, 11, 19, 39–43). In addition, previous studies have been unable to trace the kinetics of the A-ring metabolites as a result of the localization of previously used isotope labels to the C and B rings of the flavonoid backbone (36, 38). The synthesizing of a labeled C3G with a different number of $^{13}C$ atoms on the A and B rings was a major advantage in the current study.

In conclusion, the current study indicates that anthocyanins have a minimum relative bioavailability of 12.3 ± 1.3%, and their metabolites reach a 42-fold higher peak serum concentration that occurred much later than that of the parent anthocyanin. Overall, the present study indicated a much higher relative bioavailability and greater diversity of circulating metabolites than previously reported. The mechanisms of action and relative importance of these metabolites on health outcomes should be the focus of future anthocyanin research.

## REFERENCES

1. Cassidy A, O'Reilly ÉJ, Kay C, Sampson L, Franz M, Forman J, Curhan G, Rimm EB. Habitual intake of flavonoid subclasses and incident hypertension in adults. Am J Clin Nutr 2011;93:338–47.
2. de Pascual-Teresa S, Moreno DA, Garcia-Viguera C. Flavanols and anthocyanins in cardiovascular health: a review of current evidence. Int J Mol Sci 2010;11:1679–703.
3. Wallace TC. Anthocyanins in cardiovascular disease. Adv Nutr 2011;2:1–7.
4. McCullough ML, Peterson JJ, Patel R, Jacques PF, Shah R, Dwyer JT. Flavonoid intake and cardiovascular disease mortality in a prospective cohort of US adults. Am J Clin Nutr 2012;95:454–64.
5. Mink PJ, Scrafford CG, Barraj LM, Harnack L, Hong CP, Nettleton JA, Jacobs DR Jr. Flavonoid intake and cardiovascular disease mortality: a prospective study in postmenopausal women. Am J Clin Nutr 2007;85:895–909.
6. Kay CD Aspects of anthocyanin absorption, metabolism, & pharmacokinetics in humans. Nutr Res Rev 2006;19:137–46.
7. Manach C, Williamson G, Morand C, Scalbert A, Rémésy C. Bioavailability and bioefficacy of polyphenols in humans. I. Review of 97 bioavailability studies. Am J Clin Nutr 2005;81:230S–42S.
8. Mazza G, Kay C. Bioactivity, absorption, and metabolism of anthocyanins. In: Daayf F, Lattanzio V, eds. Recent advances in polyphenols research. Edtion ed. Oxford, United Kingdom: Wiley-Blackwell, 2007. [AQ13]
9. Garcia-Alonso M, Minihane A-M, Rimbach G, Rivas-Gonzalo JC, de Pascual-Teresa S. Red wine anthocyanins are rapidly absorbed in humans and affect monocyte chemoattractant protein 1 levels and antioxidant capacity of plasma. J Nutr Biochem 2009;20:521–9.
10. Kay CD, Mazza G, Holub BJ. Anthocyanins exist in the circulation primarily as metabolites in adult men. J Nutr 2005;135:2582–8.

11. Kay CD, Mazza G, Holub BJ, Wang J. Anthocyanin metabolites in human urine and serum. Br J Nutr 2004;91:933–42.

12. Milbury PE, Cao G, Prior R, Blumberg J. Bioavailablility of elderberry anthocyanins. Mech Ageing Dev 2002;123:997–1006.

13. Miyazawa T, Nakagawa K, Kudo M, Muraishi K, Someya K. Direct intestinal absorption of red fruit anthocyanins, cyanidin-3-glucoside and cyanidin-3,5-diglucoside, into rats and humans. J Agric Food Chem 1999;47:1083–91.

14. Hooper L, Kroon PA, Rimm EB, Cohn JS, Harvey I, Le Cornu KA, Ryder JJ, Hall WL, Cassidy A. Flavonoids, flavonoid-rich foods, and cardiovascular risk: a meta-analysis of randomized controlled trials. Am J Clin Nutr 2008;88:38–50.

15. Wu X, Beecher GR, Holden JM, Haytowitz DB, Gebhardt SE, Prior RL. Concentrations of anthocyanins in common foods in the United States and estimation of normal consumption. J Agric Food Chem 2006;54:4069–75.

16. Woodward G, Kroon P, Cassidy A, Kay C. Anthocyanin stability and recovery: implications for the analysis of clinical and experimental samples. J Agric Food Chem 2009;57:5271–8.

17. González-Barrio R, Edwards C, Crozier A. Colonic catabolism of ellagitannins, ellagic acid, and raspberry anthocyanins: in vivo and in vitro studies. Drug Metab Dispos 2011;39:1680–8.

18. Williamson G, Clifford M. Colonic metabolites of berry polyphenols: the missing link to biological activity? Br J Nutr 2010;104:S48–S66.

19. Nurmi T, Mursu J, Heinonen M, Nurmi A, Hiltunen R, Voutilainen S. Metabolism of berry anthocyanins to phenolic acids in humans. J Agric Food Chem 2009;57:2274–81.

20. Zhang Q, Botting N, Kay C. A gram scale synthesis of a multi-13C-labelled anthocyanin, [6,8,10,3',5'-13C5]cyanidin-3-glucoside, for use in oral tracer studies in humans. Chem Commun (Camb) 2011;47:10596–8.

21. Morrison DJ, Dodson B, Slater C, Preston T. (13)C natural abundance in the British diet: implications for (13)C breath tests. Rapid Commun Mass Spectrom 2000;14:1321–4.

22. Neveu V, Perez-Jimenez J, Vos F, Crespy V, du Chaffaut L, Mennen L, Knox C, Eisner R, Cruz J, Wishart D, et al. Phenol-Explorer: an online comprehensive database on polyphenol contents in foods. Database (Oxford) 2010;2010:bap024.

[AQ14] 23. Zhang Q, Saki Raheem K, Botting N, Slawin A, Kay C, O'Hagan D. Flavonoid metabolism: the synthesis of phenolic glucuronides and sulfates as candidate metabolites for bioactivity studies of dietary flavonoids. Tetrahedron 2012;68:4194–201.

24. Morrison DJ, O'Hara J, King RF, Preston T. Quantitation of plasma 13C-galactose and 13C-glucose during exercise by liquid chromatography/isotope ratio mass spectrometry. Rapid Commun Mass Spectrom 2011;25:2484–8.

25. Morrison DJ, Taylor K, Preston T. Strong anion-exchange liquid chromatography coupled with isotope ratio mass spectrometry using a Liquiface interface. Rapid Commun Mass Spectrom 2010;24:1755–62.

26. Slater C, Hardieck M, Preston T, Weaver LT. Analysis of tert.-butyldimethylsilyl [1-13C]palmitic acid in stool samples by gas chromatography-mass spectrometry with electron impact ionisation:

27. Shreeve WW, Cerasi E, Luft R. Metabolism of [2-'4Clpyruvate in normal, acromegalic, and HGH-treated human subjects. Acta Endocrinol (Copenh) 1970;65:155–69.

28. Haycock GB, Schwartz G, Wisotsky D. Geometric method for measuring body surface area: a height-weight formula validated in infants, children, and adults. J Pediatr 1978;93:62–6.

29. Zhang Y, Huo M, Zhou J, Xie S. PKSolver: an add-in program for pharmacokinetic and pharmacodynamic data analysis in Microsoft Excel. Comput Methods Programs Biomed 2010;99:306–14.

30. Williamson G, Manach C. Bioavailability and bioefficacy of polyphenols in humans. II. Review of 93 intervention studies. Am J Clin Nutr 2005;81(suppl):243S–55S.

31. Mullen W, Rouanet J, Auger C, Teissèdre P, Caldwell S, Hartley R, Lean M, Edwards C, Crozier A. Bioavailability of [2-(14)C]quercetin-4'-glucoside in rats. J Agric Food Chem 2008;56:12127–37.

32. Walle T, Walle UK, Halushka PV. Carbon dioxide is the major metabolite of quercetin in humans. J Nutr 2001;131:2648–52.

33. Del Rio D, Borges G, Crozier A. Berry flavonoids and phenolics:bioavailability and evidence of protective effects. Br J Nutr 2010;104 (suppl 3):S67–90.

34. Del Bò C, Ciappellano S, Klimis-Zacas D, Martini D, Gardana C, Riso P, Porrini M. Anthocyanin absorption, metabolism, and distribution from a wild blueberry-enriched diet (Vaccinium angustifolium) Is affected by diet duration in the Sprague− Dawley rat. J Agric Food Chem 2010;58:2491–7.

35. Felgines C, Krisa S, Mauray A, Besson C, Lamaison JL, Scalbert A, Mérillon JM, Texier O. Radiolabelled cyanidin 3-O-glucoside is poorly absorbed in the mouse. Br J Nutr 2010;103:1738–45.

36. Das NP, Sothy S. Studies on flavonoid metabolism. Biliary and urinary excretion of metabolites of (+)-[U-14C] catechin. Biochem J 1971;125:417.

37. Ueno I, Nakano N, Hirono I. Metabolic fate of [14C] quercetin in the ACI rat. Jpn J Exp Med 1983;53:41–50.

38. Das NP, Griffiths LA. Studies on flavonoid metabolism. Metabolism of (+)-[14C] catechin in the rat and guinea pig. Biochem J 1969;115:831–6.

39. Felgines C, Talavera S, Gonthier MP, Texier O, Scalbert A, Lamaison JL, Remesy C. Strawberry anthocyanins are recovered in urine as glucuro- and sulfoconjugates in humans. J Nutr 2003;133:1296–301.

40. Felgines C, Talavera S, Texier O, Gil-Izquierdo A, Lamaison J-L, Remesy C. Blackberry anthocyanins are mainly recovered from urine as methylated and glucuronidated conjugates in humans. J Agric Food Chem 2005;53:7721–7.

41. Vitaglione P, Donnarumma G, Napolitano A, Galvano F, Gallo A, Scalfi L, Fogliano V. Protocatechuic acid is the major human metabolite of cyanidin-glucosides. J Nutr 2007;137:2043–8.

42. Tsuda T, Horio F, Osawa T. Absorption and metabolism of cyanidin 3-O-beta-D-glucoside in rats. FEBS Lett 1999;449:179–82.

43. Ichiyanagi T, Rahman MM, Hatano Y, Konishi T, Ikeshiro Y. Protocatechuic acid is not the major metabolite in rat blood plasma after oral administration of cyanidin 3-O-[beta]-d-glucopyranoside. Food Chem 2007;105:1032–9.