**Gastrointestinal modifications and bioavailability of brown seaweed phlorotannins and effects on inflammatory markers**

Giulia Corona¹,² *, Yang Ji², Prapaporn Anegboonlap², Sarah Hotchkiss³, Chris Gill⁴, Parveen Yaqoob², Jeremy P. E. Spencer² and Ian Rowland²

¹Health Sciences Research Centre, University of Roehampton, London SW15 4JD, UK
²Department of Food and Nutritional Sciences, University of Reading, Reading RG6 6AP, UK
³CyberColloids Ltd, Carrigaline Industrial Estate, Carrigaline, County Cork P43 VR72, Republic of Ireland
⁴Northern Ireland Centre for Food & Health, University of Ulster, Coleraine BT52 1AA, UK

(Submitted 22 October 2015 – Final revision received 28 December 2015 – Accepted 7 January 2016 – First published online 16 February 2016)

**Abstract**

Brown seaweeds such as Ascophyllum nodosum are a rich source of phlorotannins (oligomers and polymers of phloroglucinol units), a class of polyphenols that are unique to Phaeophyceae. At present, there is no information on the bioavailability of seaweed polyphenols and limited evidence on their bioactivity in vivo. Consequently, we investigated the gastrointestinal modifications in vitro of seaweed phlorotannins from A. nodosum and their bioavailability and effect on inflammatory markers in healthy participants. In vitro, some phlorotannin oligomers were identified after digestion and colonic fermentation. In addition, seven metabolites corresponding to in vitro-absorbed metabolites were identified. Urine and plasma samples contained a variety of metabolites attributed to both unconjugated and conjugated metabolites (glucuronides and/or sulphates). In both urine and plasma, the majority of the metabolites were found in samples collected at late time points (6–24 h), suggesting colonic metabolism of high-molecular-weight phlorotannins, with three phlorotannin oligomers (hydroxytrifuhalol A, 7-hydroxyeckol, C-O-C dimer of phloroglucinol) identified in urine samples. A significant increase of the cytokine IL-8 was also observed. Our study shows for the first time that seaweed phlorotannins are metabolised and absorbed, predominantly in the large intestine, and there is a large inter-individual variation in their metabolic profile. Three phlorotannin oligomers present in the capsule are excreted in urine. Our study is the first investigation of the metabolism and bioavailability of seaweed phlorotannins and the role of colonic biotransformation. In addition, IL-8 is a possible target for phlorotannin bioactivity.

**Key words:** Polyphenols: Phlorotannins: Brown seaweed: Bioavailability: Metabolism: Human subjects

There has been increasing interest in the past few years on the bioactive compounds present in seaweeds¹⁻³. Traditionally, seaweeds are consumed as a food product in Asian countries and are increasingly used worldwide as ingredients for industrial applications. In Japan, over 20 species of red, green and brown algae (seaweed) are included in meals⁴⁻⁵, and daily seaweed consumption per person has remained relatively constant over the past 40 years, in the range of 1·50–3·65 kg/person per year, as reported by a range of studies⁵⁻⁷. Seaweeds are a rich source of polyphenolic compounds⁸⁻⁹, and polyphenols extracted from algae⁹⁻¹⁰ show some similarities to those found in land plants⁹⁻¹¹. Thus, the main polyphenols found in brown seaweeds are phlorotannins¹²⁻¹⁵, a type of phenolic compound only found in brown seaweeds¹⁶. Brown seaweed phlorotannins are oligomers and polymers of phloroglucinol units, and their oligomer and polymer molecular weights can greatly vary, from 126 Da to 650 kDa¹⁷, comprising up to 15% of the plant dried weight¹⁴. It has been reported that the consumption of brown algae is on average 1·342 kg/person per year, containing 66·652 g of phlorotannins/person per year and 183 mg/person per d¹⁸. Phlorotannins are classified according to the type of linkages between phloroglucinol units into four main groups: eckols (with dibenzodioxin linkages), fucols (with a phenyl linkage), fuhalols and phloroethols (with ether linkages), and fucophloroethols (with ether and phenyl linkages)¹⁹. Phlorotannins are being increasingly investigated for their vast array of bioactivities¹⁰⁻¹⁰,¹⁸ such as antioxidant¹⁹⁻²⁴, anti-inflammatory²⁰⁻²⁵, antibacterial²⁶⁻²⁸, anticancer²⁹⁻³³ and antidiabetic²⁹⁻³⁵, showing promising potential to further develop seaweed-derived products rich in bioactive components with commercial potential for food and pharma applications³⁶.

Abbreviations: DM, digestion metabolite; ESI, electrospray ionisation; GI, gastrointestinal; HMW, high-molecular-weight; LPS, lipopolysaccharide; NP-HPLC, normal-phase HPLC; RP-HPLC, reverse-phase HPLC; SPE, seaweed polyphenol extract.

* Corresponding author: Dr G. Corona, fax +44 208392 3610, email giulia.corona@roehampton.ac.uk

© The Authors 2016

British Journal of Nutrition (2016), 115, 1240–1253

doi:10.1017/S0007114516000210
Bioavailability is a critical factor influencing in vivo biological activity of polyphenols and we have reasonable understanding of the bioavailability of polyphenols from fruits and vegetables, and some of the mechanisms by which they exert beneficial effects in vitro have been determined\(^\text{(57)}\). Their ability to act as effective bioactive molecules in vitro is dependent on the extent of their biotransformation\(^\text{(24)}\) and conjugation during absorption from the gastrointestinal (GI) tract, in the liver and finally in cells\(^\text{(57)}\). Consequently, consideration must be given to the way polyphenols are absorbed and metabolised during GI digestion and colonic fermentation, and how this may have an impact on bioactivity\(^\text{(39)}\). It is noteworthy that there is no information on the bioavailability of seaweed phlorotannins, and this is a limitation to understanding their bioactivity and mechanism of action in vivo. In the absence of specific data regarding phlorotannin absorption and bioavailability, it is useful to consider the absorption and metabolism of other polyphenols as a guide\(^\text{(37)}\). In general, after ingestion of a polyphenol-rich diet, their protective effects in vivo are determined by measuring a range of suitable biomarkers, and they correlate with the absorption of polyphenols from the gut and their circulation/excretion\(^\text{(39)}\). Polyphenols can be extensively conjugated to form glucuronide, sulphate and methyl group in the gut mucosa and inner tissues\(^\text{(37,39)}\), and absorption occurs in the small intestine\(^\text{(37)}\). Polyphenols unabsorbed in the upper GI cells\(^\text{(37)}\). Consequently, consideration must be given to the way from the gastrointestinal (GI) tract, in the liver and colonic microflora and inner tissues\(^\text{(37,39)}\), and absorption occurs in the small intestine\(^\text{(37)}\). Polyphenols unabsorbed in the upper GI tract or re-excreted in the bile are extensively metabolised by colonic microflora into a wide range of low-molecular-weight phenolic acids\(^\text{(40)}\). The aim of this study was to elucidate the GI modifications of seaweed phlorotannins, and the effects on their metabolism and bioavailability. A food-grade seaweed polyphenol extract (SPE) rich in phlorotannins (from the brown seaweed Ascophyllum nodosum) was subjected to in vitro GI digestion and fermentation to examine the GI modifications occurring in the upper and lower GI tract. Furthermore, the absorption and metabolism of polyphenols in healthy subjects was investigated, after oral ingestion of a SPE capsule containing 101.89 mg of polyphenols. This amount represents an intake lower than the average daily intake of seaweed polyphenols in the Asian diet, and it is not expected to exert any cytotoxic effect\(^\text{(41)}\). The impact of absorption and GI modifications on phlorotannins anti-inflammatory potential is explored.

### Methods

#### Seaweed material

Fresh *A. nodosum* was supplied by The Hebridean Seaweed Company, Isle of Lewis, Scotland in March 2011. The seaweed biomass was harvested by hand, cleaned and then shipped refrigerated to the processing facility in France where it was immediately chopped and frozen.

#### Preparation of food-grade seaweed polyphenol extract and capsule

A novel SPE from *A. nodosum* was produced by CEVA (France) using a solvent-based extraction system that was specifically developed for this study and for use with either fresh or frozen *A. nodosum*. The solvent was a 60:40 ethanol-water mixture, which allowed for the water content of the seaweed itself. The extraction was carried out over 5 h using constant stirring and at all times protected from light. A solvent-to-seaweed ratio of 3:1 was used. The mixture was filtered to remove the supernatant, and subsequently the alcohol was removed using a rotary evaporator. A hydrometer was used to check that all of the alcohol had been removed. The final extract was recovered by centrifugation and further filtration before freeze-drying.

Approximately half of the produced extract (basic extract) was then fractionated using tangential flow ultrafiltration to produce further extracts of varying molecular-weight range and with varying polyphenol content. A blended SPE was formulated (Table 1) using 175 mg of basic extract and 50 mg of high-molecular-weight (HMW) fraction (>10 kDa cut-off) for use in the current study. Maltodextrin (175 mg) was added to the capsule formulation as an excipient. This was done in order to maximise the polyphenol content (>100 mg/d) but also to minimise the level of I to within accepted regulatory guidelines (<500 μg/d). Blending was carried out at the food-grade CEVA facilities in France. Doses of 400 mg of the SPE Ascophyllum blend were packed into white, opaque, vegetarian capsules by Irish Seaweeds, Belfast, UK and used for the clinical study. The food-grade seaweed capsule was characterised by normal-phase (NP)-HPLC (NP-HPLC) and liquid chromatography (LC)-MS analysis. Phlorotannins were quantified using the Folin–Ciocalteu Method\(^\text{(42)}\) using phloroglucinol as the standard\(^\text{(38)}\).

#### Simulated gastrointestinal digestion and fermentation

The GI digestion procedure was adapted from Mills et al\.(43) (2008) and McDougall et al\.(44) (2005). This method consists of two sequential stages: gastric digestion and small intestinal digestion followed by dialysis. A measure of 10 g of SPE was

<table>
<thead>
<tr>
<th>Extract components</th>
<th>Basic extract (mg/175 mg of extract)</th>
<th>HMW fraction (mg/50 mg of extract)</th>
<th>Blend (capsule) (mg/400 mg capsule)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyphenols</td>
<td>58.74</td>
<td>43.15</td>
<td>101.89</td>
</tr>
<tr>
<td>I</td>
<td>0.46</td>
<td>0.02</td>
<td>0.48</td>
</tr>
<tr>
<td>Maltodextrin*</td>
<td>175</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minerals</td>
<td>37.77</td>
<td>1.22</td>
<td>38.99</td>
</tr>
<tr>
<td>Fucoxanthin</td>
<td>&lt;0.001</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>Laminarin as glucose</td>
<td>10.24</td>
<td>1.64</td>
<td>11.88</td>
</tr>
<tr>
<td>Fucoidan as fucose</td>
<td>&lt;0.001</td>
<td>0.23</td>
<td>0.23</td>
</tr>
<tr>
<td>Mannitol</td>
<td>29.03</td>
<td>5.53</td>
<td>33.56</td>
</tr>
<tr>
<td>Inorganic arsenic</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Cd (LD 0.15 mg/kg)</td>
<td>&lt;LD</td>
<td>&lt;LD</td>
<td>&lt;LD</td>
</tr>
<tr>
<td>Hg (LD 0.016 mg/kg)</td>
<td>&lt;LD</td>
<td>&lt;LD</td>
<td>&lt;LD</td>
</tr>
<tr>
<td>Pb (LD 1.1 mg/kg)</td>
<td>&lt;LD</td>
<td>&lt;LD</td>
<td>&lt;LD</td>
</tr>
<tr>
<td>Sn (LD 1.7 mg/kg)</td>
<td>&lt;LD</td>
<td>&lt;LD</td>
<td>&lt;LD</td>
</tr>
</tbody>
</table>

* LD, limit of detection.  
* Maltodextrin was added to the capsule formulation as an excipient.
dissolved in 30 ml of acidified water (pH = 2), and pepsin (320 U/ml) was added. Samples were incubated at 37°C for 2 h on a shaker covered with foil to protect them from light. Aliquots of 5 ml (G) were removed. The pH was adjusted to 7.5 by adding a few drops of 6 M-NaOH, and pancreatin (4 mg/ml) and bile extracts (25 mg/ml) were added. The samples were incubated at 37°C for 2 h on a shaker. Aliquots of 5 ml (SD) were removed. Samples were transferred into the dialysis tubing (100–500 Da, cut-off, 18 ml/cm, Spectra/Por; Biotech) and dialysed overnight at 4°C against water (4 litres) to remove low-molecular-weight digestes. Aliquots of 5 ml of dialysis solution (D1) were removed. The dialysis fluid was changed and dialysis was continued for an additional 2 h. Aliquots of 5 ml of second dialysis solution (D2) were removed. Samples (SI + D) were freeze-dried and subjected to colonic fermentation (batch culture): the method was adapted from Tzounis et al.(45) Batch-culture fermentation vessels (300 ml; one vessel per treatment) were autoclaved and filled with 135 ml of sterilised basal medium. Medium was stirred and gassed overnight with O2-free N2. Before the addition of SI + D-digested extracts equivalent to 1·5 g of undigested extracts, the temperature inside the vessels was set to 37°C by a circulating water bath, and the pH was controlled at 6·8 by an Electrolab pH controller (Electrolab UK), in order to mimic conditions in the distal region of the human large intestine (anaerobic; 37°C; pH 6·8). Vessels were inoculated with 15 ml of faecal slurry (1:10, v/v), and batch cultures were run for 24 h. Samples measuring 7 ml were collected at five time points (0, 2, 4, 8 and 24 h), centrifuged at 13 000 rpm at 4°C for 10 min and the supernatants were kept. All the samples collected during the digestion and fermentation procedures were stored at −80°C until LC-MS analysis.

Study design

This study was conducted according to the guidelines laid down in the Declaration of Helsinki, and all procedures involving human subjects/patients were approved by the University of Reading Ethics Committee before initiation of the study. Written informed consent was obtained from all participants. Exclusion criteria for subjects were as follows: smokers, BMI > 18 or > 30 kg/m2, abnormal liver function and haematology, alcohol intake of > 21 U/week, GI disease or chronic GI disorders, consumption of antibiotics in previous 3 months and being pregnant. Potentially suitable participants underwent a screening process, and individuals with blood pressure > 150/90 mmHg; Hb > 125 g/l for men and > 110 g/l for women, γ-glutamyl transferase > 1·3 mlkat/l or cholesterol > 6·5 mmol/l were excluded from the study. In total, twenty-four volunteers were recruited: twelve female volunteers (six aged 18–30 years and six aged 30–65 years) and twelve male volunteers (six aged 18–30 years and six aged 30–65 years). Participants were asked to follow a low phenolic diet for 1 d before the study day (devoid of coffee, tea, fruit, vegetables, alcoholic beverages, cocoa, whole-grain and seaweed-containing products). On the day of the study, the subjects were cannulated and a baseline blood sample was taken. Participants were asked to consume one SPE capsule (400 mg) containing 101·89 mg of polyphenols. Blood samples were collected at 0, 1, 2, 3, 4, 6, 8 and 24 h after ingestion of the SPE capsule, and urine samples were collected at baseline, 0–8 and 8–24 h after the ingestion. During the day, participants were provided with a lunch and dinner of low phenolic content. The study is registered at clinicaltrials.gov (study ID: NCT02496806).

Sample collection and storage

One aliquot of blood was collected in heparin tubes and cultured immediately (whole blood culture for cytokine analysis). One aliquot of blood was collected in EDTA tubes and centrifuged at 3000 rpm for 15 min at 4°C. The plasma was separated and 1 mg/ml ascorbic acid was added as preservative. Aliquots were stored at −80°C until analysis. Total volume of collected urine was recorded, and aliquots were stored at −80°C until analysis.

Plasma sample processing for metabolite analysis

Plasma samples were prepared by following a procedure similar to the one described by Ottaviani et al.(46) A volume of 10 μl of internal standard solution (resorcinol 200 μg/ml) was added to 450 μl of plasma, and then 50 μl of 1·2 M-acetic acid was added and samples were mixed. Samples were analysed with and without enzymatic treatment (37°C, 40 min) in the presence of 1500 IU of β-glucuronidase and 50 IU of sulfatases from Helix pomatia (type H-1). A volume of 1 ml of 100% methanol acidified with 0·5% acetic acid was added, and samples were centrifuged for 15 min at 16 100 g at 4°C and supernatants were kept. This step was repeated three times (last time with 50% methanol acidified with 0·5% acetic acid), and the supernatants were dried using a SpeedVac. The pellets were dissolved with 125 μl of mobile phase and transferred to vials for reverse-phase (RP)-HPLC (RP-HPLC) analysis.

Urine sample processing for metabolite analysis

Urine samples were prepared according to a procedure similar to the one described by Ottaviani et al.(46). Briefly, 10 μl of internal standard solution (resorcinol 200 μg/ml) was added to 250 μl of urine. Samples were analysed with and without enzymatic treatment (37°C, 40 min), in the presence of 1500 IU of β-glucuronidase and 50 IU of sulfatases from H. pomatia (type H-1). A volume of 1 ml of 100% methanol acidified with 0·5% acetic acid was added, samples were mixed and centrifuged for 15 min at 16 100 g at 4°C, and supernatants were transferred to a new tube and dried on a SpeedVac. Dried samples were re-suspended on 125 μl of mobile phase, completely dissolved, centrifuged and transferred to vials for RP-HPLC analysis and LC-MS analysis.

Normal-phase HPLC analysis

The phlorotannins in the food-grade SPE used to produce the capsule were analysed by NP-HPLC analysis(46) using an HPLC 1100 series equipped with LiChrospher Si60-5 column (250 mm x 4·0 mm ID, 5 μm particle size from Hichrom (LISP60-5-250A0F), fitted with a guard column LiChrospher Si60-5 from HICHROM (LISP60-5-10C5)). The mobile phase contained A: 82%
dichloromethane+2% methanol+2% acetic acid in water and B: 96% methanol+2% acetic acid in water, and it was pumped through the column at a rate of 1 ml/min. A volume of 10 μl of samples was injected and analysed by the gradient programme, which was (min/%B) as follows: 0, 30/17, 65/30, 70/87, 60/87, 80/0, 105/0 for detection of all compounds. The compounds were detected at a wavelength of 208 nm. All data were analysed by the ChemStation software. The phloroglucinol standard was injected at 0–100 μg/ml, and phlorotannins in the capsules were analysed as phloroglucinol equivalents.

Reverse-phase HPLC analysis

The analysis of plasma and urine samples was carried out with a Hewlett-Packard 1100 series liquid chromatograph (Hewlett-Packard), as previously described. Samples were analysed by RP-HPLC using a Nova-Pak C18 column (4.6 × 250 mm) with 4 μm particle size. The temperature of the column was maintained at 30°C. The mobile phases consisted of a mixture of 5% aqueous methanol in 0.1% hydrochloric acid 5μl (A) and a mixture of aqueous acetone-tritile 50 in 0.1% hydrochloric acid 5μl (B), and they were pumped through the column at a rate of 0.7 ml/min. The following gradient system was used (min/%B): 0/5, 5/5, 40/50, 55/100, 59/90/100, 60/5, with 10 min post-run for both compound and metabolite detections. The eluent was monitored by photodiode array detection at 280 nm and spectra of products obtained over the 200–600 nm range. Peaks were characterised by their retention time and spectrum characteristics. A calibration curve of phloroglucinol was constructed using authentic standards (0–1–100 μg/ml), and in each case they were found to be linear with correlation coefficients of 0.995. Metabolites were quantified as phloroglucinol equivalents.

Liquid chromatography-MS analysis

LC-MS analysis was conducted to analyse the food-grade seaweed capsule, the urine samples and the digested materials, and it was carried out in the negative ion mode using LC-MS/MS utilising electrospray ionisation (ESI), as previously described. Characterisation was achieved using LC-MS/MS utilising ESI. This consisted of an Agilent 1200 HPLC system equipped with a binary pump, degasser, auto-sampler, thermostat, column heater, photodiode array detector and an Agilent 1100 series LC/MSD Mass Trap Spectrometer (Agilent Technologies UK). Separation of samples was achieved using a Zorbax SB C18 column (2.1 × 100 mm; 1.8μm) (Agilent), and HPLC conditions were as follows: injection volume, 1 μl; column temperature, 25°C; binary mobile system, (A) 0.1% aqueous formic acid and (B) 0.1% of formic acid in acetonitrile; and flow rate, 0.2 ml/min. A series of linear gradients were used for separation (min/%B): 0/0, 3/10, 15/40, 40/70, 50/70, 65/10. MS was performed in the negative ion mode (scan range, m/z 100–1000 Da; source temperature, 350°C). All solvents used were of LC-MS grade.

Cytokine production

Blood samples collected during the clinical intervention (baseline, 1, 2, 4, 6 and 8 h) into heparin tubes were immediately cultured as follows: 500-μl blood aliquots were mixed with 500 μl of Roswell Park Memorial Institute (RPMI) medium containing antibiotics on a twenty-four-well plate, and lipopoly-saccharide (LPS) (1 μg/ml) or vehicle (control group) was added before incubation at 37°C for 24 h. At the end of the culture period, samples were centrifuged at 2000 g for 5 min, and the supernatants were collected and kept at −20°C until analysis for inflammatory cytokine levels. The supernatants were collected and stored at −20°C. Cytokines (IL-1β, IL-6, IL-8, IL-10 and TNF-α) in the supernatants were measured using Luminex xMAP Technology using commercially available Fluorokine MAP kits (R&D systems), and data were analysed on the xPONENT software. Final data are presented as the difference between LPS-treated and unstimulated control.

Statistical analysis

The statistical evaluation of the results was performed by one-way ANOVA, followed by a Bonferroni post hoc test using GraphPad InStat version 5 (GraphPad Software). Significant changes are indicated as P < 0.05.

Results

Seaweed polyphenol extract characterisation

The chromatogram (Fig. 1) illustrates the trace obtained by NP-HPLC with diode array detection after injecting a water solution of the SPE. The chromatogram shows a number of peaks (20–70 min) representing different HMW phlorotannins, the characteristic phenolics in brown seaweeds. Longer phlorotannin polymers, which consisted of more hydroxy groups, resulted in tighter attachment to the column material. Consequently, shorter compounds were released earlier than longer compounds. Owing to a lack of phlorotannin standards and the complexity of the oligomeric and polymeric forms, the calibration curve of phloroglucinol was used to quantify all the phlorotannins contained in the SPE as phloroglucinol equivalents. The SPE comprised a wide range of molecular weights of phloroglucinol derivatives with a total phlorotannin concentration of 312 μg/mg quantified as phloroglucinol equivalents. Further characterisation of the SPE was achieved with LC-MS/MS (Fig. 2) using ESI. The data were collected in a non-targeted manner, by acquiring full spectrum data in negative ion mode from m/z 100 to 1000. The data were then analysed by searching for the theoretical mono-isotopic masses corresponding to possible phlorotannin oligomers and the

![Fig. 1. Chromatographic separation of phlorotannins contained in the seaweed extract by normal-phase HPLC with diode array detection (288 nm).](https://www.cambridge.org/core/asset/2f4c8a582b4f7a02f1c83b18f00c4c01/79a3d6e5b948902f6f1760b37f9c9a5377d861c0)
presence of ions (1-6), which could correspond to phlorotannins (Fig. 2). The ion 1 with [M-H]- at m/z 405 corresponded to the trimer hydroxytrifuhalol A, whereas the MS2 fragment m/z 387 corresponded to the loss of one molecule of water (−18), a characteristic pattern of phlorotannin fragmentation. Compound 2 ([M-H]- at m/z 497) was considered to be a phlorotannin tetramer composed of 4 phloroglucinol units, such as tetrafucol or fucodiphlorethol, and also in this case the fragment m/z 479 corresponds to the loss of a molecule of water (−18), whereas the fragment m/z 353 corresponds to the loss of water (−18) and a phloroglucinol unit (−126), in accordance with analytical profiles recently described in positive ion mode by Wang et al. and by Ferreres et al. The ion 3 has a [M-H]- at m/z 247 corresponding to a C-O-C dimer of phloroglucinol, as previously indicated by Nwosu et al. The ion 4 (387) corresponds to the trimer 7-hydroxyeckol, and we observe the presence of a fragment at m/z 369 deriving from the loss of one molecule of water. Isomers 5 and 6 with [M-H]- at m/z 249 were also observed, which can correspond to the dimers diphlorethol and difucol.

**In vitro digestion and characterisation**

Because of the lack of commercially available standards for phlorotannins and the complexity of the oligomers and polymers in the extract, the analysis of phlorotannins and their metabolites is required and involves a combination of approaches. Similarly to other polyphenol classes, phlorotannins may undergo extensive modification by phase I and phase II enzymes and the colonic microbiota during their transit through the GI tract, and the implication of such metabolic modifications on the bioactivity of phlorotannins has not been investigated yet. Consequently, we subjected the SPE to in vitro digestive and fermentative processes. An in vitro gastric and ileal digestion and colon microbial fermentation of the SPE was initially conducted, followed by dialysis to simulate absorption into the circulation. The MS spectra and fragmentations of the compounds detected in the samples were studied (Fig. 3). After in vitro digestion and fermentation procedures, the samples were analysed by LC-MS/MS using ESI in negative ion mode, as previously described, searching for the theoretical mono-isotopic masses corresponding to the low-molecular-weight phlorotannins previously identified in the capsule (Fig. 2). We were able to identify molecular ions and fragments corresponding to hydroxytrifuhalol A (405), the C-O-C dimer of phloroglucinol (247), the dimer diphlorethol/difucol (249) and 7-hydroxyeckol (387), also found after colonic fermentation. In addition, in digested and fermented samples subjected to dialysis to mimic absorption into the circulation, we reported the presence of seven compounds (digestion metabolite (DM)1-7) corresponding to in vitro-absorbed metabolites.

**Plasma and urine analysis**

The food-grade SPE was given to healthy subjects (Fig. 4) in the form of a capsule (400 mg) containing 101.89 mg of...
The bioavailability of seaweed phlorotannins

Fig. 3. Liquid chromatography (LC)-MS analysis in negative ion mode of the seaweed extract subjected to in vitro gastrointestinal digestion, colonic fermentation and dialysis to mimic absorption. (a) LC-MS spectra and fragmentation of in vitro-digested materials. (b) Summary of LC-MS analysis of the in vitro-digested materials. DM, digestion metabolite. SIM, small intestinal metabolite; FM, fermentation metabolite.
polyphenols, and blood and urine samples were analysed for phlorotannin metabolites. HPLC-diode array detector (DAD) analysis of the plasma (Fig. 5) and urine (Fig. 6) samples with and without glucuronidase/sulfatase treatment showed the presence of a variety of metabolites absent in the baselines (before the seaweed capsule ingestion) in samples from fifteen volunteers out of twenty-four. In plasma, the total level of phlorotannins and their metabolites ranges from 0·011 to 7·757 µg/ml, and in urine 0·15 to 33·52 µg/ml are excreted. Some metabolite peaks were present in samples with and without enzymatic treatment, and therefore could be assigned to unconjugated metabolites. Some other metabolite peaks were present only in samples without enzymatic treatment or were only appearing in samples enzymatically treated, and were attributed to conjugated forms (glucuronides and/or sulphates) and their enzymatically released unconjugated forms. In urine, some metabolites were found in samples collected at 0–8 h after capsule ingestion, but the majority of the metabolites were found in samples collected at 8–24 h. Some metabolites, such as urine metabolite (UM)6 and UM7, show similar UV spectra characteristics and might therefore be structurally related (Fig. 6). In plasma (Fig. 5), some metabolites were found in samples collected at 2, 3 and 4 h after capsule ingestion, but the majority of the metabolites were found in samples collected at later time points (6–24 h). This could be the result of poor absorption of the HMW phlorotannins in the upper GI tract, resulting in them reaching the colon and undergoing fermentation to lower-molecular-weight derivatives by the colonic microbiota. In addition, urine samples were subjected to LC-MS/MS (Fig. 7) using ESI, as previously described, searching for the theoretical mono-isotopic masses corresponding to the low-molecular-weight phlorotannins previously identified in the capsule (Fig. 2). We were able to identify molecular ions and fragments corresponding to hydroxytrifluhalol A, 7-hydroxyeckol and the C-O-C dimer of phloroglucinol, which corresponded to the HPLC metabolite UM3. In addition, we reported the presence of two ions (289 and 377) corresponding to metabolites that we characterised in samples from SPE subjected to in vitro GI digestion and fermentation (DM4 and DM7, Fig. 3), as previously detailed.

Ex vivo cytokine production

The ex vivo production of cytokines (IL-1β, IL-6, IL-8, IL-10 and TNF-α) relative to baseline levels in cultured blood collected at various time points (0, 1, 2, 3, 4, 6 and 8 h) during the intervention study (LPS treated – unstimulated controls) is reported in Fig 8. The amounts of TNF-α and IL-10 remained quite stable over time, as well as the amount of all cytokines at 1 and 2 h. IL-6 levels were observed to decrease at later time points (4–8 h) without reaching statistical significance (P > 0·05). The levels of both IL-1β and IL-8 were observed to increase from 3 to 8 h after the intervention; however, the statistical analysis revealed that the only significant change from baseline levels was the increase of IL-8 at 8 h.

Discussion

Polyphenols are ubiquitously found in plants and comprise a major part of a daily human diet. Over the past 20 years, significant data have emerged with regard to the potential beneficial effects of several classes of phenolic compounds against a number of chronic diseases. In addition, a reasonable understanding has been gained of the bioavailability of many polyphenol classes, and this will be important for understanding the mechanisms by which they exert such benefits in vivo. The interest in marine sources of phenolic compounds is recent, and knowledge on phlorotannin bioavailability is still lacking. The analysis of phlorotannins is challenging because of the high range of molecular weight present, and their characterisation is complicated further by the lack of commercially available standards. Chromatography techniques coupled to diode array and MS detection have been applied to the analysis of phlorotannins, and the advantages/disadvantages of their use are described by Stevensz et al. NP-HPLC is a separation mode that is commonly used for polyphenol separation; however, the very high polarity of phlorotannins would cause them to elute with little or no retention because of the lack of interaction with the nonpolar stationary phase. NP-HPLC is more advantageous for retaining compounds with very high polarity, and the NP-HPLC methodology developed by Koivikko was more suitable than RP-HPLC for the separation of phlorotannins from the brown algae Fucus vesiculosus. Thus, we initially analysed the phlorotannins in our SPE by NP-HPLC using a method adapted from Koivikko et al. As expected, the SPE comprised a wide range of molecular weights (20–70 min), with abundance of very HMW phlorotannins eluting at later retention time (50–70 min) in our normal-phase method. MS detection can provide higher sensitivity and be advantageous to identify specific phlorotannins in the extract without commercially available standards; however, NP-HPLC solvents such as...
dichloromethane are not suitable for MS analysis\(^{(52)}\), because they would result in poor ionisation and therefore significantly reduce sensitivity\(^{(51,53)}\).

Nwosu et al\(^{(29)}\) characterised a phlorotannin extract from \textit{A. nodosum} by RP-HPLC using a C18 column: the bound sample eluted in a unresolved set of peaks, and with MS detection in negative ion mode they were able to assign the detected \(m/z\) spectra to a series of phlorotannin structures\(^{(29)}\). Ferreres et al\(^{(50)}\) identified twenty-two different phlorotannins belonging to the eckol and fucophloroethol groups in four seaweed species belonging to the order Fucales (genus \textit{Cystoseira} and \textit{Fucus}), with RP-HPLC separation combined with DAD-ESI-multiple-stage MS detection\(^{(50)}\). By using an equivalent RP-HPLC separation method coupled to ESI-MS analysis in negative ion mode, we were able to identify some phlorotannin oligomers such as hydroxytrifuhalol A, tetrafucol, fucodiphloroethol, C-O-C dimmer of phloroglucinol, 7-hydroxyeckol, diphloretol and difucol. The fragmentation patterns of the oligomers

<table>
<thead>
<tr>
<th>RP-HPLC analysis of seaweed metabolites in plasma samples</th>
<th>Metabolite</th>
<th>Mean (µg/ml)</th>
<th>SD</th>
<th>n volunteers</th>
<th>Time (h)</th>
<th>Enz-</th>
<th>Enz+</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>PM1</td>
<td>2.16</td>
<td>2.01</td>
<td>2</td>
<td>4; 24</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>0.000</td>
<td>PM2</td>
<td>0.95</td>
<td>1</td>
<td>24</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>0.000</td>
<td>PM3</td>
<td>0.07</td>
<td>1</td>
<td>8</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>0.000</td>
<td>PM4</td>
<td>0.07</td>
<td>2</td>
<td>3; 24</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>0.000</td>
<td>PM5</td>
<td>0.05</td>
<td>7</td>
<td>3; 4; 6; 8; 24</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>0.000</td>
<td>PM6</td>
<td>2.82</td>
<td>2</td>
<td>24</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>0.000</td>
<td>PM7</td>
<td>0.03</td>
<td>1</td>
<td>3</td>
<td>No</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>0.000</td>
<td>PM8</td>
<td>0.03</td>
<td>1</td>
<td>24</td>
<td>No</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>0.000</td>
<td>PM9</td>
<td>0.06</td>
<td>2</td>
<td>3; 8; 24</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>0.000</td>
<td>PM10</td>
<td>0.01</td>
<td>2</td>
<td>24</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>0.000</td>
<td>PM11</td>
<td>0.02</td>
<td>1</td>
<td>24</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>0.000</td>
<td>PM12</td>
<td>0.04</td>
<td>1</td>
<td>24</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>0.000</td>
<td>PM13</td>
<td>0.05</td>
<td>3</td>
<td>24</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>0.000</td>
<td>PM14</td>
<td>0.04</td>
<td>1</td>
<td>4</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>0.000</td>
<td>PM15</td>
<td>0.01</td>
<td>1</td>
<td>2</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>0.000</td>
<td>PM16</td>
<td>0.02</td>
<td>3</td>
<td>2; 3</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>0.000</td>
<td>PM17</td>
<td>0.04</td>
<td>1</td>
<td>4</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>0.000</td>
<td>PM18</td>
<td>0.03</td>
<td>5</td>
<td>6; 24</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5. HPLC analysis of plasma samples for seaweed metabolites. (a) HPLC chromatograms (268 nm) and UV spectra showing examples of metabolites in plasma. (b) Summary of seaweed metabolites present in plasma samples. PM, plasma metabolite; RP-HPLC, reverse-phase HPLC.
that we identified are in agreement with some recently published data in the field\(^{45,50}\). Recently, Steevensz et al.\(^{34}\) characterised the phlorotannins of five brown algae species by ultrahigh-pressure liquid chromatography operating in ‘mixed-mode’ (hydrophilic interaction liquid chromatography mode) combined with high-resolution MS. The methodology proposed

<table>
<thead>
<tr>
<th>RT (min)</th>
<th>Metabolite</th>
<th>Mean (mg)</th>
<th>sd</th>
<th>n volunteers</th>
<th>Time (h)</th>
<th>Enz-</th>
<th>Enz+</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-9</td>
<td>UM1</td>
<td>15.25</td>
<td>1.39</td>
<td>2</td>
<td>0–8; 8–24</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>10-4</td>
<td>UM2</td>
<td>10.77</td>
<td>4.29</td>
<td>7</td>
<td>8–24</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>14-2</td>
<td>UM3</td>
<td>16.66</td>
<td>0.89</td>
<td>2</td>
<td>8–24</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>16-7</td>
<td>UM4</td>
<td>2.94</td>
<td>1.82</td>
<td>3</td>
<td>8–24</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>17-7</td>
<td>UM5</td>
<td>0.67</td>
<td></td>
<td>1</td>
<td>8–24</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>18-7</td>
<td>UM6</td>
<td>5.58</td>
<td>0.17</td>
<td>2</td>
<td>8–24</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>24-1</td>
<td>UM7</td>
<td>9.85</td>
<td></td>
<td>1</td>
<td>8–24</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>29-6</td>
<td>UM8</td>
<td>0.30</td>
<td></td>
<td>1</td>
<td>8–24</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>30-8</td>
<td>UM9</td>
<td>0.51</td>
<td></td>
<td>1</td>
<td>8–24</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>33-0</td>
<td>UM10</td>
<td>1.26</td>
<td></td>
<td>1</td>
<td>8–24</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>33-1</td>
<td>UM11</td>
<td>1.28</td>
<td>0.09</td>
<td>2</td>
<td>8–24</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>34-3</td>
<td>UM12</td>
<td>0.63</td>
<td>0.15</td>
<td>2</td>
<td>8–24</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>36-5</td>
<td>UM13</td>
<td>0.61</td>
<td>0.55</td>
<td>6</td>
<td>8–24</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>41-8</td>
<td>UM14</td>
<td>1.45</td>
<td>0.86</td>
<td>8</td>
<td>0–8; 8–24</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>43-7</td>
<td>UM15</td>
<td>0.25</td>
<td></td>
<td>1</td>
<td>8–24</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>45-5</td>
<td>UM16</td>
<td>0.69</td>
<td></td>
<td>1</td>
<td>8–24</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>46-1</td>
<td>UM17</td>
<td>0.25</td>
<td></td>
<td>1</td>
<td>8–24</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>46-7</td>
<td>UM18</td>
<td>0.70</td>
<td></td>
<td>1</td>
<td>8–24</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Fig. 6. HPLC analysis of urine samples for seaweed metabolites. (a) HPLC chromatograms (268 nm) and UV spectra showing examples of metabolites in urine. (b) Summary of seaweed metabolites present in urine samples. UM, urine metabolite; RP-HPLC, reverse-phase HPLC.
by this research group proved to be accurate for profiling phlorotannins based on their degree of polymerisation, and it was demonstrated to be an effective separation mode for low-molecular-weight phlorotannins, up to 6 kDa.[34]. Phlorotannin characterisation is a challenging and complex task, which is complicated by the lack of commercially available standard compounds; thus, chromatography separation coupled to MS detection can help to elucidate phlorotannin

![Fig. 7. Liquid chromatography (LC)-MS analysis in negative ion mode of urine samples. (a) LC-MS spectra and fragmentation of phlorotannins found in urine samples. (b) Summary of LC-MS analysis of the urine samples. DM, digestion metabolite.](image-url)
complexity, and its application to the analysis of clinical samples from feeding trials, as well as the use of simplified in vitro digestion systems, can help elucidate their beneficial health properties and the bioactive circulating forms. The SPE was subjected to in vitro-simulated GI digestion and fermentation, followed by dialysis to simulate as close as possible their absorption and biotransformation. The obtained materials were analysed by LC-MS for a comparative characterisation of the phlorotannin metabolites. LC-MA analysis of the digested and fermented SPE has indicated the presence of some oligomeric phlorotannin metabolites. LC-MS analysis, we were able, for the first time, to confirm the presence of some phlorotannin oligomers in urine, more specifically hydroxytrifluhalol A, 7-hydroxyeckol, and the C-O-C dimer of phloroglucinol. Interestingly, two of the urine metabolites (m/z 289 and 377) were present in the in vitro-digested samples (DM4 and DM7).

There were substantial differences between volunteers in the pattern of phlorotannin metabolites. Such inter-individual differences have been observed for other polyphenols and have been attributed to differences in gut microbiota composition and the expression of metabolising enzymes (54, 55).

A secondary aim of our work has been to determine whether the SPE could modulate inflammatory events in the blood, following the absorption of phlorotannin metabolites and because of their presence in the circulation. Polyphenols can exert numerous antioxidant and non-antioxidant functions of relevance in chronic disease development, and many of them have an important in vivo role in inflammatory events in the blood, through a transcriptional mechanism primarily regulated by NF-κB (60). Redox signalling mechanisms are known to play a role in the regulation of such events, with reactive oxygen species being able to promote IL-8 production in mononuclear phagocytes and other cell types, with significant increased levels of the cytokine after 8 h compared with baseline.

IL-8 is an important inflammatory factor of the cysteine-intervening amino acid-cysteine (CXC) chemokine family, involved in the amplification of inflammatory signals (59). IL-8 secretion is induced by TNF-α through a transcriptional mechanism primarily regulated by NF-κB (60). Redox signalling mechanisms are known to play a role in the regulation of such events, with reactive oxygen species being able to promote IL-8 production and secretion (38, 53), whereas oxygen radical scavengers are proven to inhibit IL-8 production in LPS-stimulated human whole blood (22). Dietary polyphenols such as catechin (53) and curcumin (28) have also been shown to specifically interfere with IL-8 gene expression through inhibition of NF-κB activation (61). In consequence, we would have expected circulating seaweed polyphenol metabolites to
potentially be able to inhibit IL-8 secretion. Our results have given a preliminary indication that the cytokine IL-8 is a possible target for phlorotannin metabolites. However, a significant increase in IL-8 levels at 8 h after the intervention was observed, in parallel with the presence of phlorotannin metabolites in plasma and urine samples. A recent study from our group investigated the influence of a polyphenol-rich intervention on inflammation as primary outcome. A randomised, double-blind, placebo-controlled, cross-over acute intervention was conducted, and cytokine levels (IL-8) were measured with the same \textit{ex vivo} experimental protocol. The results showed a time-dependent increase in IL-8 release compared with baseline, in accordance with our findings. Thus, the postprandial \textit{ex vivo} IL-8 production was significantly attenuated by the intervention compared with the control, with a parallel appearance in the circulation of polyphenol metabolites. Our trial was a single-group interventional study primarily designed to investigate the bioavailability of seaweed phlorotannins; however, on the basis of this preliminary indication on their anti-inflammatory potential, not sufficient to draw any conclusion, a chronic placebo-controlled intervention has been conducted to investigate the anti-inflammatory effect in deeper detail.

The main limitations of this study arise from the phlorotannin complexity and lack of commercially available analytical standards, potentially leading to possible quantification inaccuracy as phloroglucinol equivalents. The lack of analytical standards also implies a limited capability for method development, especially for the analysis of plasma, urine and digested materials. In future, the availability of standards could allow a higher degree of method optimisation and the development of specific solid-phase ion procedures for sample clean-up and concentration.

The development of more recently explored analytical applications to phlorotannins, such as hydrophilic interaction liquid chromatography\(^{32}\) and NMR\(^{33}\), could facilitate the development of more suitable protocols that could lead to full identification of metabolites and improvements in phlorotannin metabolite quantification. In addition, the bioaccessibility of polyphenols in the form of a capsule/extract might differ greatly from the bioaccessibility of the same compounds in a food matrix\(^{62}\). Future work will be needed to determine the potential effects on bioavailability of different food matrices and also any effects of cooking and/or processing.

Nevertheless, the present work has for the first time started to shed light on the role of colonic biotransformation on phlorotannin bioavailability, and its implication for their health benefits \textit{in vivo}. Our results provide a basis for further investigating the seaweed-derived bioactive components in the body after ingestion; this information is necessary to understand their mechanism of action \textit{in vivo}.

Acknowledgements

This work is part of the SWAFAX project (no. 262519), funded by the European Commission under the Capacities Programme (FP7).

We would like to thank all the SWAFAX project partners for their contribution, including Marigot, Hebridean Seaweed, Mesosystem S.L., Cycolloids and the University of Ulster.

G. C., J. P. E. S., P. Y. and I. R. designed the research. G. C. organised and coordinated all parts of the clinical trial and analytical work. S. H. overviewed the preparation of seaweed materials, extracts and capsules. P. A. aided running the clinical trial. Y. J. aided with the analysis of metabolites in plasma and urines. G. C. analysed and summarised all the data. G. C. drafted the manuscript. C. G., I. R., S. H. and P. Y. revised the manuscript. I. R. had primary responsibility for final content.

The authors declare that there are no conflicts of interest.

References


