Identification of (poly)phenol treatments that modulate the release of pro-inflammatory cytokines by human lymphocytes

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(Submitted 23 July 2015 – Final revision received 22 January 2016 – Accepted 12 February 2016 – First published online 17 March 2016)

Abstract
Diet rich in fruits and vegetables (FV), which contain (poly)phenols, protect against age-related inflammation and chronic diseases. T-lymphocytes contribute to systemic cytokine production and are modulated by FV intake. Little is known about the relative potency of different (poly)phenols in modulating cytokine release by lymphocytes. We compared thirty-one (poly)phenols and six (poly)phenol mixtures for effects on pro-inflammatory cytokine release by Jurkat T-lymphocytes. Test compounds were incubated with Jurkat cells for 48 h at 1 and 30 µM, with or without phorbol ester treatment at 24 h to induce cytokine release. Three test compounds that reduced cytokine release were further incubated with primary lymphocytes at 0·2 and 1 µM for 24 h, with lipopolysaccharide added at 5 h. Cytokine release was measured, and generation of H2O2 by test compounds was determined to assess any potential correlations with cytokine release. A number of (poly)phenols significantly altered cytokine release from Jurkat cells (P<0·05), but H2O2 generation did not correlate with cytokine release. Resveratrol, isorhamnetin, curcumin, vanillic acid and specific (poly)phenol mixtures reduced pro-inflammatory cytokine release from T-lymphocytes, and there was evidence for interaction between (poly)phenols to further modulate cytokine release. The release of interferon-γ induced protein 10 by primary lymphocytes was significantly reduced following treatment with 1 µM isorhamnetin (P<0·05). These results suggest that (poly)phenols derived from onions, turmeric, red grapes, green tea and açai berries may help reduce the release of pro-inflammatory mediators in people at risk of chronic inflammation.

Key words: Jurkat cells; Curcumin; Resveratrol; Isorhamnetin; TNFα

(Poly)phenols, comprising flavonoids and related compounds, are produced by plants that are widely consumed in the human diet. A high dietary intake of fruits and vegetables, which are rich in (poly)phenols, has been linked through epidemiological studies with reduced risk for diseases that are associated with age-related chronic inflammation, including CVD(1–5), type II diabetes(4,5), cancer(6–9), Alzheimer’s disease(10) and Parkinson’s disease(11). Supplementation with (poly)phenol-rich foods or purified (poly)phenols has been reported to reduce levels of pro-inflammatory cytokines in the human circulation, including TNFα and IL-6, cytokines that have been implicated in the pathogenesis of chronic inflammatory diseases(12–14). T-lymphocytes significantly contribute to the release of pro- and anti-inflammatory cytokines both into the circulation and within tissues. Dietary (poly)phenols may influence the behaviour of T-lymphocytes and other cells via redox signalling, that is the production or quenching of free radicals, or by interactions with specific proteins(15). The production of H2O2 by (poly)phenols through autoxidation catalysed by transition metals is known to influence the behaviour of cells in culture(16,17), but the effects of (poly)phenol-induced H2O2 generation on T-lymphocytes and the relevance of this in the modulation of cytokine release are not well understood. A majority of (poly)phenols have low bioavailability in vivo as parent compounds(18,19), therefore, recent interest has been focused on metabolites of dietary (poly)phenols, including the methylated, glucuronidated, and sulphated conjugates that are produced by intestinal and liver cells, and the aromatic acids produced by the colonic bacterial flora(20–22).

We aimed to compare thirty-one individual (poly)phenols for their effects on the release of inflammatory cytokines by Jurkat CD4+ T-lymphocytes. We examined some key dietary (poly)
phenols and a number of metabolites, including specifically a substantial number of low molecular weight colonic catabolites. Following this initial screen, three anti-inflammatory compounds were selected for further investigation of their effects on cytokine release by primary peripheral blood mononuclear cell (PBMC)-derived human lymphocytes. We further aimed to assess the generation of \(\text{H}_2\text{O}_2\) in cell culture media by these (poly)phenols and to assess whether \(\text{H}_2\text{O}_2\) generation significantly influences cytokine release or growth of Jurkat CD\(^4\) T-lymphocytes in vitro. The question of the most appropriate doses of (poly)phenols to be used in in vitro studies is controversial within the field. Following dietary intake, (poly)phenols and the individual metabolites/catabolites can be detected in the circulation with \(C_{\text{max}}\) values generally at ns or low µM concentrations, whereas following supplementation with purified compounds or enriched food extracts values of up to 20-50 µM have been reported. For an individual with a typical dietary intake of multiple fruits and vegetables, numerous (poly)phenol metabolites/catabolites coexist in the circulation at any one time. Whether mixtures of different (poly)phenols, each present at low doses, interact in their effects on cytokine release by lymphocytes has not been clear. We therefore also investigated the effects of six different mixtures of (poly)phenols on the release of pro-inflammatory cytokines by Jurkat T-lymphocytes, in order to determine whether multiple (poly)phenols at lower doses have additive or potentially synergistic effects compared with those of single (poly)phenols.

Methods

Chemicals and materials

Reagents were purchased from Sigma-Aldrich unless stated otherwise. Sigma-Aldrich also supplied resveratrol, quercetin, isorhamnetin, 3-O-methylquercetin, curcumin, (−)-epigallocatechin-3-O-gallate, pelargonidin-3-O-glucoside, cyanidin-3-O-glucoside, chlorogenic acid (3-Ocaffeoylquinic acid), punicalagin, phloroglucinol (1,3,5-trihydroxybenzene), pyrogallol (1,2,3-trihydroxybenzene), catechin (1,2-dihydroxystilbene), protocatechuic acid (3,4-dihydrobenzoic acid), 4-hydroxybenzoic acid, homoprotocatechuic acid (3',4'-dihydroxyphenylacetic acid), vanillic acid (3-methoxy-4-hydroxybenzoic acid), homovanillic acid (3'-methoxy-4'-hydroxyphenylacetilic acid), 4'-hydroxyphenylacetic acid, 4'-hydroxymandelic acid, 5-(3'-carboxymethoxyphenyl)-2-(4-sulfophenyl)-2H-tetrazolium, inner salt and phenazine methosulfate reagent (Promega) was added to each well and the plate was incubated for 24 h at 37°C and 5 % \(\text{CO}_2\). Test compounds were not removed during PMA/PHA treatment, and thus the total incubation period with each (poly)phenol was 48 h. Each treatment was performed in quadruplicate alongside matched vehicle controls. Mixed (poly)phenol treatments were conducted using the same protocol, except that each of the four compounds in each mixture was added at either 0.25 or 7.5 µM, thus achieving either a 1 or 30 µM total concentration of (poly)phenols.

Measurement of viable cell number

Following incubations with test compounds and stimulation agents, cell numbers were quantified by transferring 100 µl cell suspension from each well to a flat-bottomed, clear, ninety-six-well plate. A sample of 20 ml of 3-(4,5-dimethylthiazol-2-yl)-5-(3-carboxymethoxyphenyl)-2-(4-sulfophenyl)-2H-tetrazolium, inner salt and phenazine methosulfate reagent (Promega) was added to each well and the plate was incubated for 90 min at 37°C and 5 % \(\text{CO}_2\). Following incubation, absorbance was read at 490 nm on a BMG Labtech Spectrostar Nano plate reader. Viable cell numbers were estimated from a standard curve determined by haemocytometer counting with 0.02 % (w/v) trypan blue stain.

Primary lymphocyte isolation, cell culture and treatment

Primary human lymphocytes were obtained from a healthy 45-year-old female donor after obtaining written consent, by withdrawal of 50 ml blood from the antecubital vein using a butterfly needle and syringe. The procedure was approved by the National Research Ethics service, UK (reference 11/NW/0313), as well as by the University of Liverpool and Royal Liverpool and Broadgreen University Hospitals NHS Trust ethics committees. Whole blood was separated over Ficoll-Paque Premium density gradient medium (GE Healthcare Life Sciences) by centrifugation at 370 \(\text{g}\) for 30 min without rotor braking. PBMC were isolated from the buffy layer, centrifuged again at 370 \(\text{g}\) for 10 min without rotor braking, then resuspended in FBS containing 10 % DMSO and cryogenically stored. The PBMC were later thawed, washed once in medium at 37°C in a humidified 5 % \(\text{CO}_2\) incubator in Roswell Park Memorial Institute (RPMI)-1640 medium containing phenol red supplemented with 10 % fetal bovine serum (FBS) and 2 µM-\(\text{L}\)-glutamine. Jurkat cells were seeded at 2 \(\times\) 10\(^6\) cells/ml in a forty-eight-well plate (500 µl culture volume) and treated with each test compound at 1 or 30 µmol/l by dilution from 5 µM stocks in dimethyl sulfoxide (DMSO). The same volume of DMSO only was added to vehicle control wells. After 24 h of incubation with test compounds, 25 ng/ml phorbol 12-myristate 13-acetate (PMA) by 1:1000 dilution from a 25 µg/ml DMSO stock solution and 5 µg/ml phytohaemagglutinin (PHA) by 1:1000 dilution from a 5 mg/ml stock solution in water were added to some wells, and vehicle controls were treated with DMSO at 1:1000 dilution. Typically, the equivalent volume of DMSO added to each well was 0.5 µl. Co-treatment with PMA (a protein kinase C activator) and PHA (a T-cell receptor cross-linking agent) has been widely used to stimulate cytokine production by T-lymphocytes\(^{22}\). Following PMA/PHA treatment, plates were incubated for 24 h at 37°C and 5 % \(\text{CO}_2\). Test compounds were not removed during PMA/PHA treatment, and thus the total incubation period with each (poly)phenol was 48 h. Each treatment was performed in quadruplicate alongside matched vehicle controls. Mixed (poly)phenol treatments were conducted using the same protocol, except that each of the four compounds in each mixture was added at either 0.25 or 7.5 µM, thus achieving either a 1 or 30 µM total concentration of (poly)phenols.
(RPIM-1640 supplemented with 10% FBS and 2 mmol/l of L-glutamine) to remove DMSO, resuspended in the same medium and then cultured at 37°C and 5% CO2 in a T25 tissue culture flask laid horizontally. After 5 d of incubation to allow monocytes to adhere to the culture flask, the lymphocyte-enriched suspension cells were seeded to a forty-eight-well plate at 2 × 10⁶ cells/ml in 150 µl total volume. After 24 h of incubation at 37°C/5% CO2, the lymphocytes were treated with test compounds (resveratrol, isorhamnetin and curcumin) diluted from 5 mmol/l DMSO stocks to a final concentration of either 0.2 or 1 µmol/l, or the same volume of DMSO only as the vehicle control. Lymphocytes were incubated for 5 h at 37°C/5% CO2; next, 20 ng/ml lipopolysaccharide (LPS) was added without removing media and the cells were incubated for a further 19 h. Following the total 24 h of incubation, cell numbers and viability were determined by trypan blue staining.

Fig. 1. Structures of (poly)phenols used in cell culture experiments. Confirmed metabolic relationships are shown: ▲, metabolite of quercetin(23,24); □, metabolite of (–)-epigallocatechin-3-O-gallate(25,26); ●, metabolite of cyanidin-3-O-glucoside(27); ○, metabolite of pelargonidin-3-O-glucoside(28); and ▴, metabolite of chlorogenic acid(29). The phenolic catabolite structures are approximately ordered from those produced in the small intestine (top) to those derived in the proximal gastrointestinal tract via colonic catabolism (bottom).

(Poly)phenols modulate T-lymphocyte cytokine release
(0·02% w/v final concentration trypan blue; TC-20 automated cell counter, Bio-Rad) and media were harvested for quantification of cytokines.

Quantification of cytokines in lymphocyte cell culture media

Cells were pelleted by centrifugation at 400 g for 5 min. The culture media supernatants were immediately frozen at −80°C and remained frozen until they were thawed for analysis using a BioPlex 200 multi-protein analysis platform (Bio-Rad) and BioPlex bead sets targeting the human cytokine analytes detailed in Table 1. The analysis was performed according to the manufacturer’s instructions. All reagents were purchased from Bio-Rad.

Cytokine concentrations were calculated by comparing raw fluorescence emission values with a standard curve diluted from a solution of mixed recombinant cytokine proteins (Bio-Rad). Cytokine concentrations were then normalised for the number of viable cells in the culture at the end of treatment, as quantified by trypan blue exclusion assay. Each time a Jurkat cell treatment experiment was performed, four test compounds were assayed together with a matched vehicle control (either DMSO alone or DMSO with PMA/PHA stimulation at 24 h, as appropriate). Data were normalised to yield percentage changes from vehicle controls by dividing values measured from (poly)phenol-treated cells by the value measured from the matched vehicle control and multiplying by 100. To ascertain whether mixtures of (poly)phenols may synergistically modulate Jurkat T-lymphocyte cytokine release, six mixtures were analysed, each comprised of four (poly)phenols. The results obtained following treatment of Jurkat T-lymphocytes with the (poly)phenol mixtures were compared with the averaged effects of those individual compounds. The total concentration of mixed (poly)phenols and their metabolites was constant at 1 or 30 µmol/l to enable closer comparison with the individual compound treatments.

Luminescent plate reader analysis of H₂O₂ generation

Using an opaque, black, ninety-six-well plate, 5 mM-DMSO stock solutions of thirty-two different (poly)phenols (the same) were diluted to a stock solutions of thirty-two different (poly)phenols (the same normalised to cell number for cytokine measurements. Jurkat and converted into the rates of H₂O₂ generation (nmol/min) quantify an emission wavelength of 585 nm. Kinetic reactions were performed using raw data for cell number and H₂O₂ generation and data normalised to cell number for cytokine measurements. Jurkat

Results

Phorbol 12-myristate 13-acetate/phytohaemagglutinin

24-h treatment stimulates the release of pro-inflammatory cytokines by Jurkat CD4⁺ T-lymphocytes

Jurkat CD4⁺ T-lymphocytes were treated with the protein kinase C activator PMA and the plant-derived lymphocyte mitogen PHA for 24 h to induce an inflammatory response and cytokine release. The PMA/PHA-stimulated cells showed a significant increase in the release of several pro-inflammatory cytokines compared with vehicle control treatments (Table 1). We chose to focus on IL-2, IL-8 and TNFα for further experiments because of the relative magnitude of their induction by PMA/PHA treatment and the well-defined roles of each of these proteins as physiologically important pro-inflammatory cytokines.

Polyphenol catabolites modulate growth and cytokine release by Jurkat CD4⁺ T-lymphocytes

After treatment with colonic catabolites of polyphenols (phenolic acids) for 48 h, we measured the density of viable Jurkat CD4⁺ T-lymphocytes in culture and the concentrations of the pro-inflammatory cytokines IL-2, IL-8 and TNFα in the cell culture media. Comparisons between (poly)phenol treatments and vehicle controls revealed multiple effects on growth and cytokine release (Fig. 2). The low molecular weight (110–139 g/mol) catabolites catechol, phloroglucinol and 4-hydroxybenzoic acid caused significant declines in cell number (P < 0·05; one-way ANOVA with Dunnett’s post hoc test) and significantly induced release of IL-2, IL-8 and TNFα in the cell culture media. Comparisons between (poly)phenol treatments and vehicle controls revealed multiple effects on growth and cytokine release (Fig. 2). The low molecular weight (110–139 g/mol) catabolites catechol, phloroglucinol and 4-hydroxybenzoic acid caused significant declines in cell number (P < 0·05; one-way ANOVA with Dunnett’s post hoc test) and significantly induced release of IL-2, IL-8 and TNFα in the cell culture media. Comparisons between (poly)phenol treatments and vehicle controls revealed multiple effects on growth and cytokine release (Fig. 2). The low molecular weight (110–139 g/mol) catabolites catechol, phloroglucinol and 4-hydroxybenzoic acid caused significant declines in cell number (P < 0·05; one-way ANOVA with Dunnett’s post hoc test) and significantly induced release of IL-2, IL-8 and TNFα in the cell culture media. Comparisons between (poly)phenol treatments and vehicle controls revealed multiple effects on growth and cytokine release (Fig. 2). The low molecular weight (110–139 g/mol) catabolites catechol, phloroglucinol and 4-hydroxybenzoic acid caused significant declines in cell number (P < 0·05; one-way ANOVA with Dunnett’s post hoc test) and significantly induced release of IL-2, IL-8 and TNFα in the cell culture media. Comparisons between (poly)phenol treatments and vehicle controls revealed multiple effects on growth and cytokine release (Fig. 2). The low molecular weight (110–139 g/mol) catabolites catechol, phloroglucinol and 4-hydroxybenzoic acid caused significant declines in cell number (P < 0·05; one-way ANOVA with Dunnett’s post hoc test) and significantly induced release of IL-2, IL-8 and TNFα in the cell culture media. Comparisons between (poly)phenol treatments and vehicle controls revealed multiple effects on growth and cytokine release (Fig. 2). The low molecular weight (110–139 g/mol) catabolites catechol, phloroglucinol and 4-hydroxybenzoic acid caused significant declines in cell number (P < 0·05; one-way ANOVA with Dunnett’s post hoc test) and significantly induced release of IL-2, IL-8 and TNFα in the cell culture media. Comparisons between (poly)phenol treatments and vehicle controls revealed multiple effects on growth and cytokine release (Fig. 2). The low molecular weight (110–139 g/mol) catabolites catechol, phloroglucinol and 4-hydroxybenzoic acid caused significant declines in cell number (P < 0·05; one-way ANOVA with Dunnett’s post hoc test) and significantly induced release of IL-2, IL-8 and TNFα in the cell culture media. Comparisons between (poly)phenol treatments and vehicle controls revealed multiple effects on growth and cytokine release (Fig. 2). The low molecular weight (110–139 g/mol) catabolites catechol, phloroglucinol and 4-hydroxybenzoic acid caused significant declines in cell number (P < 0·05; one-way ANOVA with Dunnett’s post hoc test) and significantly induced release of IL-2, IL-8 and TNFα in the cell culture media. Comparisons between (poly)phenol treatments and vehicle controls revealed multiple effects on growth and cytokine release (Fig. 2). The low molecular weight (110–139 g/mol) catabolites catechol, phloroglucinol and 4-hydroxybenzoic acid caused significant declines in cell number (P < 0·05; one-way ANOVA with Dunnett’s post hoc test) and significantly induced release of IL-2, IL-8 and TNFα in the cell culture media. Comparisons between (poly)phenol treatments and vehicle controls revealed multiple effects on growth and cytokine release (Fig. 2).
T-lymphocytes (Fig. 3). Three polyphenols – resveratrol, isorhamnetin and curcumin – significantly reduced pro-inflammatory cytokine release at both 1 and 30 µmol/l and in both unstimulated and PMA/PHA-stimulated cells (P < 0.05; one-way ANOVA with Dunnett’s post hoc test). Curcumin treatment at 30 µmol/l led to the greatest reductions in pro-inflammatory cytokine release, with IL-2 release decreased by 96% and TNFα release ablated to undetectable

Table 1. Cytokines induced by phorbol 12-myristate 13-acetate/phytohaemagglutinin (PMA/PHA) treatment of Jurkat CD4⁺ T-lymphocytes
(Mean values with their standard errors)

<table>
<thead>
<tr>
<th>Cytokines</th>
<th>Untreated control (pg/ml) Mean SEM</th>
<th>DMSO vehicle control (pg/ml) Mean SEM</th>
<th>24 h PMA/PHA stimulated (pg/ml) Mean SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eotaxin-1</td>
<td>ND</td>
<td>2.85, 1.47</td>
<td>0.48, 0.56</td>
</tr>
<tr>
<td>GM-CSF</td>
<td>ND</td>
<td>ND</td>
<td>5.81*, 0.39</td>
</tr>
<tr>
<td>IFN-γ</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>IL-1β</td>
<td>ND</td>
<td>13.45, 1.39</td>
<td>14.40, 1.41</td>
</tr>
<tr>
<td>IL-2</td>
<td>21.55</td>
<td>0.35</td>
<td>0.80, 0.66</td>
</tr>
<tr>
<td>IL-6</td>
<td>ND</td>
<td>35.25, 2.88</td>
<td>34.22, 2.32</td>
</tr>
<tr>
<td>IL-7</td>
<td>0.3</td>
<td>0.06</td>
<td>3.52, 0.66</td>
</tr>
<tr>
<td>IL-8</td>
<td>35.25</td>
<td>2.88</td>
<td>1612.68*, 92.71</td>
</tr>
<tr>
<td>IL-12p70</td>
<td>ND</td>
<td>ND</td>
<td>7.68*, 1.52</td>
</tr>
<tr>
<td>IL-13</td>
<td>ND</td>
<td>ND</td>
<td>259.55*, 12.36</td>
</tr>
<tr>
<td>MCP-1</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>TNFα</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
</tbody>
</table>

GM-CSF, granulocyte macrophage-colony stimulating factor; IFN, interferon; MCP, monocyte chemoattractant protein.

* P < 0.05 compared with DMSO vehicle control.

Fig. 2. Heat map showing the effects of phenolic acids on cytokine release and growth by Jurkat CD4⁺ T-lymphocytes. Compounds are ordered by molecular weight from the lowest weight (top) to the highest weight (bottom). Data are presented as percentage differences from matched vehicle controls following 48 h of treatment. Treatment and control experiments were performed with or without 25 ng/ml phorbol 12-myristate 13-acetate (PMA) and 5 µg/ml phytohaemagglutinin (PHA) stimulation at 24 h. TNFα could not be measured in the absence of PMA/PHA stimulation. * Mean value was significantly different compared with vehicle controls (P < 0.05; one-way ANOVA with Dunnett’s post hoc test). No significant effects were observed following treatment with caffeic acid, ferulic acid, isoferulic acid, 5-(3'-hydroxyphenyl) propionic acid, 5-(3',4'-dihydroxyphenyl) propionic acid, 5-(3'-methoxy-4'-hydroxyphenyl) propionic acid, homoprotocatechuic acid, 3-(4'-hydroxyphenyl) lactic acid, hippuric acid or 4'-hydroxyhippuric acid. Examples of the data from which these heat maps are derived are provided in the online Supplementary data to allow an assessment of the variability observed in these studies.

T-lymphocytes...
concentrations in PMA/PHA-stimulated cells ($P<0.05$; one-way ANOVA with Dunnett’s post hoc test). The flavan-3-ol (−)-epigallocatechin-3-O-gallate, and the anthocyanins pelargonidin-3-O-glucoside and cyanidin 3-O-glucoside, significantly promoted the growth of Jurkat CD4+ T-lymphocytes at 1 µmol/l ($P<0.05$; one-way ANOVA with Dunnett’s post hoc test). Chlorogenic acid and 3-O-methylquercetin showed some anti-proliferative effects on Jurkat CD4+ T-lymphocytes under all treatment conditions, although statistical significance was only achieved for the effects of 3-O-methylquercetin ($P<0.05$; one-way ANOVA with Dunnett’s post hoc test).

Mixtures of (poly)phenols interact to modulate cytokine release

To assess potential interactions between test compounds in modulating cytokine release, we prepared several mixtures of (poly)phenols: mixture 1 representing low-molecular weight colonic catabolites such as catechol, chlorogluclon, 4-hydroxybenzoic acid and protocatechuic acid; mixture 2 representing mid-molecular weight colonic catabolites such as 4-hydroxyxymandelic acid, 4-hydroxyphenylacetic acid, 5-(3’-hydroxyphenyl) propionic acid and 3-(4’-hydroxyphenyl) lactic acid; mixture 3 representing a mixture of dietary polyphenols such as (−)-epigallocatechin-3-O-gallate, pelargonidin-3-O-glucoside, cyanidin-3-O-glucoside and punicalagin; mixture 4 representing polyphenols and high molecular weight hydroxycinnamate metabolites, such as dihydroferulic acid, feruloylglycine, quercetin and 3-O-methylquercetin; mixture 5 representing a mixture of hydroxycinnamate derivatives derived from chlorogenic acid after the consumption of coffee, such as caffeic acid, ferulic acid, isoflavone acid and isoferuloylglycine; and mixture 6 representing compounds derived from apple cider, such as hippuric acid, tyrosol, 4’-hydroxyhippuric acid and chlorogenic acid. We measured cytokine release from Jurkat CD4+ T-lymphocytes following 48 h of incubation with each mixture at a total concentration of 1 or 30 µmol/l, with or without stimulation with PMA/PHA at 24 h. For comparison, the results previously obtained for cytokine release following treatment with each individual compound were averaged to generate a prediction of the effects expected if there were no interactions between compounds (i.e. a null hypothesis that there were no synergistic effects). The results illustrated in Fig. 4 indicate that five of the six test mixtures significantly reduced pro-inflammatory cytokine release in comparison with results anticipated from simple addition of the effects observed for individual compounds ($P<0.05$; one-way ANOVA with Dunnett’s post hoc test).
Anti-inflammatory polyphenols modulate cytokine release by peripheral blood mononuclear cell-derived human lymphocytes

We investigated the polyphenols resveratrol, isorhamnetin and curcumin, which had been identified to be the most effective in reducing cytokine release from among the panel of (poly)phenols that we screened in Jurkat CD4+ T-lymphocytes, to determine whether their inhibitory effects on pro-inflammatory cytokine release were sustained in PBMC-derived human lymphocytes (Fig. 5). The results suggest trends (i.e. $P<0.09$) towards decreased IL-6, interferon-γ induced protein 10 (IP-10) and TNFα release following treatment with resveratrol, isorhamnetin and curcumin at 0.2 or 1 µM. The reduction in IP-10 release after treatment with 1 µM isorhamnetin was statistically significant ($P<0.05$, one-way ANOVA with Dunnett’s post hoc test).

(Poly)phenols produce $H_2O_2$ in cell culture media

Some (poly)phenols have been reported to generate $H_2O_2$ in cell culture media (16,17). To quantify $H_2O_2$ production, we conducted kinetic spectrophotometry assays using Amplex red reagent, which is converted to fluorescent resoruflavin following oxidation by $H_2O_2$. Production of $H_2O_2$ was detected for sixteen of the thirty-two test compounds (Fig. 6(a)). $H_2O_2$ production was detected from the hydroxybenzene derivatives catechol and pyrogallol, the phenylacetic acid homoprotocatechuic acid, the hydroxycinnamates caffeic acid and dihydrocaffeic acid, and the ellagitannin punicalagin, whereas other test compounds produced no detectable levels of $H_2O_2$. Comparisons were also made to assess the effects of phenol red in the culture media, which showed that rates of $H_2O_2$ production were 24 (SEM 2) % lower in RPMI-1640 medium containing phenol red than in RPMI-1640 medium without phenol red (data not shown in detail).
A number of previous studies have examined the potential effects of various polyphenols on cytokine release (28-30), and a number of dietary components including curcumin, resveratrol, genistein and epigallocatechin have been shown to modulate the release of pro-inflammatory cytokines from cells in culture (31). Various mechanisms of action have been proposed including inhibition of NF-κB, inhibition of prostanooids, inhibition of AMP-activated protein kinase (AMPK) and mitogen-activated protein kinase (MAPK) pathways and antioxidant effects (32). There has been a great deal of interest in the bioavailability of dietary polyphenols, as the non-metabolised compounds are only found in the circulation at ns to low µM concentrations. Compounds such as flavonoids are absorbed in the small intestine and appear in the circulation as glucuronoids, sulphates and methylated metabolites, but these are rapidly removed from the bloodstream (32); however, substantial amounts of the unconjugated compounds pass into the colon where they are converted to lower molecular weight catabolites such as phenolic acids by colonic microflora (33). Relatively little is known about the potential anti-inflammatory effects of these lower molecular weight phenolic acids following absorption, and this was a major aim of the present study.

Polyphenols were routinely examined at final concentrations of either 1 or 30 µM, reflecting concentrations that may potentially be achieved in the circulation through ingestion of foodstuffs or supplements, respectively. Our data showed that several (poly)phenol treatments modulated the release of pro-inflammatory cytokines (IL-2, IL-8 and TNFα) from Jurkat human CD4+ T-lymphocytes. The Jurkat cell line was originally derived from an adolescent male with acute lymphoblastic leukaemia and they are widely used as a model for pro-inflammatory cytokine release (34). Jurkat CD4+ T-lymphocytes were incubated with test compounds at 1 and 30 µM either non-stimulated or stimulated with PMA/PHA. We were interested to investigate both lower and higher dose ranges based on previous reports of differential effects between low- and high-dose (poly)phenols in vivo (35). The most potent anti-inflammatory compounds from our experiments in Jurkat CD4+ T-lymphocytes wereisorhamnetin (a flavonol that occurs as a glycoside in apples, onions and green tea), curcumin (from the Indian spice turmeric) and resveratrol (which is present in the skin of red, purple and black grapes and in especially high concentrations in Itadori tea).

The low molecular weight phenolic acids (Fig. 2) were generally less effective at reducing cytokine release than the unconjugated polyphenols, although some reductions in IL-2 release were seen with vanillic acid, tyrosol and 4-hydroxymandelic acid. Vanillic acid is a catabolite of multiple dietary polyphenols, including those found in wheat and blackcurrant juice (36), and is also present at high concentrations in açaí berries (37,38). Vanillic acid significantly reduced IL-2 release from non-stimulated Jurkat CD4+ T-lymphocytes at 1 µmol/l, which is within the range of concentrations previously reported in human plasma (39), suggesting that vanillic acid may be a physiologically relevant anti-inflammatory metabolite of dietary polyphenols.

Following ingestion of (poly)phenol-rich foodstuffs, a range of (poly)phenols, conjugates and catabolites are absorbed into the circulation. It is not understood whether the exposure of CD4+ T-lymphocytes to mixtures of these compounds may elicit different responses in comparison with the same compounds applied individually. To begin to address this issue, we treated
Jurkat CD4+ T-lymphocytes with six different mixtures of (poly)phenols. The mixtures of compounds used were selected as representative of low molecular weight colonic metabolites (mix 1), mid-molecular weight colonic catabolites (mix 2), dietary polyphenols (mix 3), polyphenols and high-molecular weight hydroxycinnamate metabolites (mix 4), hydroxycinnamate derivatives derived from chlorogenic acid produced after the consumption of coffee (mix 5) and compounds potentially derived from apples (mix 6). Of these, five mixtures reduced cytokine release more than that predicted based on the cumulative effects of individual compounds. In contrast, mixture 1 was found to be relatively pro-inflammatory and comprised low molecular weight catabolites that individually induced pro-inflammatory cytokine release. Thus, we speculate that there may be synergistic anti-inflammatory effects of some polyphenols when they are present in foodstuffs, and
the data obtained generally support this. Demonstration of true synergy between bioactive materials such as drugs requires a rigorous statistical approach(39), which we do not have the dose–response data to undertake for the large group of polyphenols that were studied; however, the data presented appear to indicate the possibility of such synergistic effects and warrant further investigation.

It has been reported that (poly)phenols produce H2O2 in cell culture media due to autooxidation catalysed by transition metals such as Fe and Cu and that this may influence the responses of cells in culture(17,40). We measured the production of H2O2 by different (poly)phenols and related compounds in RPMI-1640 medium containing 10% FBS using the Amplex red-HRP technique. This assay is specific for H2O2 in simple solutions and has been widely used to examine H2O2 release by cells and sub-cellular fractions of cells(41). H2O2 generation was found to vary between compounds, with certain phenolic catabolites producing relatively large amounts of H2O2 and others producing no detectable H2O2. Analysis of H2O2 generation by (poly)phenols in comparison with their chemical structures indicated that, in accordance with theoretical predictions(40), molecules with orthohydroxy groups on adjacent carbons of a benzene ring tended to generate H2O2. However, protocatechuic acid and 3-O-methylquercetin, which have benzene ring orthohydroxy groups, generated negligible H2O2, and moderate H2O2 generation was detected from isorhamnetin and resveratrol, which do not have orthohydroxy groups, implying that other aspects of the chemical structure also influence H2O2 generation. The average rate of H2O2 generation for these compounds in RPMI-1640 medium was 5-6 nmol H2O2/µmol (poly)phenol per min. We investigated whether H2O2 generation by each test compound correlated with their effects on the release of IL-2, IL-8 or TNFα by Jurkat CD4+ T-lymphocytes or the growth of Jurkat cultures. A correlation was identified between H2O2 production and IL-8 release by CD4+ T-lymphocytes that were not stimulated with PMA/PHA. Interestingly, previous studies have indicated that IL-8 production is subject to modulation by redox signalling(44) and can be induced by extracellular H2O2 in epithelial cell lines via activation of the redox-sensitive transcription factors activator protein-1 (AP-1) and NF-κB(42,43). Our results suggest that with PMA/PHA stimulation the influence of H2O2 on IL-8 release appears to become negligible. IL-2 and TNFα release and cell proliferation showed no clear relationship with H2O2 generation in non-stimulated or PMA/PHA-stimulated Jurkat CD4+ T-lymphocytes. Halliwell et al.(44,45) have also pointed out that the absence of any detection of H2O2 generation by a compound in cell culture cannot be equated to the stability of the compound as some polyphenols were observed to rapidly degrade and autoxidise in the absence of detectable H2O2 generation. Thus, our studies indicate a lack of correlation between in vitro H2O2 generation and effects of the compound on cytokine release, but do not exclude other cell culture artifacts that may have influenced the data obtained.

We chose to undertake a limited proof-of-principle study to investigate the potential anti-inflammatory effects of isorhamnetin, curcumin and resveratrol in primary PBMC-derived human lymphocytes. Cells were pre-treated with 1 or 30 µM polyphenol for 5 h, followed by stimulation of cytokine release using LPS stimulation and incubation for a total period of 24 h. We observed a significant reduction in IP-10 release following treatment with 1 µM isorhamnetin, and there was also a trend (P = 0.07) towards reduced TNFα release with the same treatment. These studies were undertaken using lymphocytes from a single donor and clearly require confirmation using cells from a larger group of donors, but this approach was considered out with the remit of the present study due to the large variability in cytokine release from lymphocytes obtained from different donors.

In conclusion, we have shown that (poly)phenols modulate the release of cytokines by Jurkat CD4+ T-lymphocytes under resting and chemically activated conditions. Some compounds were found to have anti-inflammatory effects, while others were pro-inflammatory, and the effects varied with dose, suggesting that some dietary (poly)phenols may be beneficial for the prevention or management of chronic inflammatory conditions. We identified isorhamnetin, curcumin, resveratrol and vanillic acid as negative regulators of pro-inflammatory cytokine release in Jurkat CD4+ T-lymphocytes, and also showed that 1 µM isorhamnetin reduced pro-inflammatory cytokine release by primary human lymphocytes. Use of mixtures of (poly)phenols also suggested that they may act synergistically to modulate cytokine release by Jurkat CD4+ T-lymphocytes. Taking into account the main dietary sources of the compounds, our data support a potential anti-inflammatory role for (poly)phenols derived from red, purple and black grapes, turmeric, whole wheat, black-currants, apples and onions, and suggest that individuals at risk of chronic inflammation, such as older people, may benefit from supplementing their diets with isorhamnetin, resveratrol, curcumin and vanillic acid or with food sources that yield these bioactive molecules.

Acknowledgements

The authors are grateful to Melanie Sinclair for the excellent technical support.

This work was supported by a grant from the Biotechnology and Biological Sciences Research Council (BBSRC) through the BBSRC Diet Research Industry Club, grant no. BB/005994/1. The funder had no role in the design, analysis or writing of this article.

M. J. J., A. M. A., A. C., S. B. L. and F. Mc. A. were involved in formulating the research question and designing the study; C. T. F. and S. R. carried out the study; C. T. F., S. R., M. J. J., A. M. A. and S. B. L. analysed the data; C. T. F. wrote the first draft of the manuscript; and all the authors edited the final version of the manuscript.

S. B. L. is employed by Unilever plc. None of the authors has any conflicts of interest to declare.

Supplementary material

For supplementary material/s referred to in this article, please visit http://dx.doi.org/10.1017/S0007114516000805
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References


