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Iodide modulates protein damage induced by the inflammation-associated heme enzyme myeloperoxidase

Luke F. Gamon a, Simon Dieterich a, Marta T. Ignasiak a,b, Verena Schrameyer c, Michael J. Davies a,c,*

a Dept. of Biomedical Sciences, University of Copenhagen, Copenhagen, Denmark
b Faculty of Chemistry, Adam Mickiewicz University, and Wielkopolska Center for Advanced Technologies Poznan, Poland
c Marine Biological Section, Department of Biology, University of Copenhagen, Denmark

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ABSTRACT

Iodide ions (I −) are an essential dietary mineral, and crucial for mental and physical development, fertility and thyroid function [1], where it is the major substrate for the heme enzyme thyroid peroxidase (also known as thyroperoxidase or iodide peroxidase), which generates the key hormones triiodothyronine (T3) and thyroxine (T4), from tyrosine (Tyr) residues present on thyroglobulin. I − deficiency results in hypothyroidism, impaired mental and physical development, decreased fertility rate, and goiter [2]. While there are risks associated with excess consumption, I − supplementation represents a simple, cheap and highly beneficial intervention [3].

I − is also a substrate for other mammalian heme peroxidases, including myeloperoxidase (MPO), a key enzyme released from intracellular storage granules of activated neutrophils, monocytes and some tissue macrophages, as part of innate immune defence against invading pathogens [4,5]. MPO generates the highly reactive and damaging oxidant hypochlorous acid (HOCI) from hydrogen peroxide (H2O2) and chloride ions (Cl −) in order to kill bacteria, yeast and other foreign materials, and low levels of MPO are known to be associated with chronic infections [4,5]. However, MPO can also oxidize other anions (e.g. Br −, SCN −, I −, NO2 −) as well as organic substrates [4,6,7].

Inappropriate production of HOCl and other oxidizing species by MPO (e.g. via sterile inflammation, excessive or inappropriate stimulation of the immune system) has been linked to a number of human inflammatory pathologies, including cardiovascular diseases, cystic fibrosis, asthma, kidney disease and a number of degenerative neurological conditions including Parkinson’s and Alzheimer’s diseases.

1. Introduction

Iodide (I −) is an essential dietary mineral which plays a key role in thyroid function [1], where it is the major substrate for the heme enzyme thyroid peroxidase (also known as thyroperoxidase or iodide peroxidase), which generates the key hormones triiodothyronine (T3) and thyroxine (T4), from tyrosine (Tyr) residues present on thyroglobulin. I − deficiency results in hypothyroidism, impaired mental and physical development, decreased fertility rate, and goiter [2]. While there are risks associated with excess consumption, I − supplementation represents a simple, cheap and highly beneficial intervention [3].

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amongst others [4,5,8-11]. MPO is released extracellularly (i.e. into phagolysosomes or externally to the cell), and is known to bind avidly to negatively-charged macromolecules including proteins, proteoglycans and glycosaminoglycans of the extracellular matrix (ECM) [12,13].

HOCl reacts with high rate constants with biological targets, and particularly proteins [14,15], and would therefore not be expected to diffuse large distances from its site of generation [16]. This is likely to result in marked damage to ECM materials to which it is bound, or those in close proximity. Considerable data support this hypothesis, with extensive damage detected on ECM materials at sites of inflammation, including within the artery wall during the development of atherosclerosis [17]. Thus up to 70% of the oxidized proteins detected in human atherosclerotic lesions has been reported to be ECM derived [18], and considerable evidence also exists for modification of other extracellular materials including plasma proteins, and low- and high-density lipoproteins [19-22]. The ECM plays a critical role as the major load-bearing and structural component of tissues and is also a key determinant of cell binding, proliferation and migration, a reservoir for growth factors and cytokines, and a major modulator of enzyme activity and function [23,24]. Evidence has been presented for the presence of MPO mRNA, protein and enzymatic activity in cardiovascular lesions, together with evidence for protein damage and a strong association between the extent of HOCl-mediated damage and the severity of disease [8,25-27]. The detection of MPO in the shoulder regions of atherosclerotic lesions, which are susceptible to rupture (the major cause of many heart attacks and strokes) indicates that the damage induced by this enzyme may play a major role in such events [28,29]. Furthermore, strong associations have been reported between the levels of MPO and the diagnosis and severity of cardiovascular disease, with the levels of this enzyme being both diagnostic of the disease, and prognostic of adverse outcomes [30-32]. Consistent with these data, recent work has highlighted the potential of molecular imaging of MPO in determining high-risk atherosclerotic plaques [33,34].

Modulation of MPO activity have been proposed as a therapeutic approach in inflammatory diseases, as inhibition may reduce MPO-derived oxidative damage [35]. Thus both suicide and competitive inhibitors of MPO (e.g. benzoic acid hydrazides [36] and thioxanthines [37]), and alternative substrates (e.g. nitroxides [38], acetaminophen/paracetamol [39]) have been examined as potential modulators of MPO-derived oxidative damage [reviewed [10,40]]. Whilst Cl⁻ is the most abundant MPO substrate, its oxidation by Compound I is relatively slow compared to Br⁻, I⁻, and SCN⁻ with apparent second order rate constants, at pH 7.0, of 2.5 × 10⁴, 1.1 × 10⁶, 7.2 × 10⁶, and 9.6 × 10⁷ M⁻¹ s⁻¹ for Cl⁻, Br⁻, I⁻ and SCN⁻ respectively [7]. Oxidation of SCN⁻ generates hypohiodynamic acid (HOSCN) [41]. HOSCN is a less powerful and less reactive oxidant than HOCl, with a high specificity for thiols (RSSH, both free and in proteins), though these reactions occur at modest rates (k ~ 10⁴ vs ~10⁸ M⁻¹ s⁻¹ for reaction of Cys with HOSCN and HOCl, respectively) [42]. Increasing the concentration of SCN⁻ alters the ratio of HOCl to HOSCN formed by MPO, and can decrease biological damage [41,43,44]. SCN⁻ supplementation (via drinking water) of mice that express human MPO decreases the size of atherosclerotic lesions present in their arteries when fed a high-fat, high-cholesterol diet [45]. In addition, a retrospective analysis of people who suffered a first myocardial infarction with a subsequent 12 year follow-up, indicated that the lowest rates of subsequent all-cause mortality were in the group with low MPO levels and high SCN⁻, and that high levels of SCN⁻ were associated with decreased mortality [46]. The extent of this effect cannot be ascertained completely, as this population contained both non-smokers, as well as ex- and current smokers, with the smokers have a known and significantly elevated risk of cardiovascular disease. However, despite this confounding factor, consideration of the data as a whole indicates that increasing SCN⁻ levels in vivo may afford protection against the development or progression of atherosclerosis.

Oxidation of I⁻ by Compound I of MPO is only marginally slower than for SCN⁻, and the resulting hypoiodynamic acid (HOI) has a much lower redox potential than HOCl (0.78 vs 1.28 V). Thus HOI would be expected to be both selective and less damaging than HOCl [47]. Several experimental and epidemiological studies have provided evidence for a protective effect of I⁻ in cardiovascular disease, but the underlying biochemical mechanism(s) are unclear [48]. Low urinary I⁻ concentrations have been associated with coronary artery disease in the North American National Health and Nutrition Examination Study (NHANES) [49], and recent work has shown that I⁻ can protect heart tissue against reperfusion injury-induced damage in a murine model [50]. This has been proposed to be due to metabolic changes [50], but MPO has also been strongly associated with reperfusion induced tissue injury as a result of neutrophil accumulation and activation after O₂ deprivation [51]. A role for I⁻ in modulating MPO-induced damage has poorly studied probably as a result of its low systemic concentration (< 1 μM for I⁻, 100 nM for Cl⁻, 20–80 μM for SCN⁻) [52], though there is abundant evidence that I⁻ levels can be significantly elevated by interventions [53,54]. In the light of these data, we hypothesised that I⁻ might reduce oxidative damage induced by MPO, when I⁻ levels are elevated over typical physiologic levels. Here we provide evidence in support of this hypothesis, with increased I⁻ concentrations modulating protein damage induced by MPO. These findings illustrate the potential of I⁻ to minimize damage associated with MPO-mediated damage and chronic inflammation.

2. Materials and methods

2.1. Chemicals and reagents

Unless otherwise stated, all chemicals were purchased from commercial sources and used as received. UPLC buffers were prepared using HPLC grade methanol (VWR) and tetrahydrofuran (Chromosolv Plus, Sigma Aldrich). Aqueous solutions were prepared using MilliQ water and buffers were prepared from 0.5 M sodium phosphate buffer at pH 7.4, or PBS, and chelex-treated prior to use to remove trace metal ions. Cl⁻ and I⁻ solutions were prepared using NaCl and KI (Sigma Aldrich). The concentration of stock H₂O₂ and HOCl solutions (Sigma Aldrich) were determined spectrophotometrically (H₂O₂ in H₂O, ε₂₄₀ 43.6 M⁻¹ cm⁻¹; HOCl in 0.5 M NaOH, ε₃₉₂ 350 M⁻¹ cm⁻¹). Immunoblotting and ELISA were performed using the following monoclonal antibodies (mAb): anti-fibronectin A17 (ab26245, Abcam), anti-fibronectin A32 (CSI 005-32-02, Thermo Fisher Scientific), 2D109G (raised against HOCl-modified protein; a kind gift from A. Prof Ernst Malle, Medical University of Graz, Austria) and anti-dityrosine (Clone 1C3 monoclonal antibody, Nordic Biosite) [55]. Detection of immune complexes from immunoblotting was achieved with ECL anti-rabbit IgG horseradish peroxidase-linked whole antibody (NA934V, GE Healthcare UK). Detection for ELISA was achieved with a polyclonal rabbit anti-mouse IgG alkaline phosphate conjugated antibody (ab70743, Abcam).

2.2. Treatment of fibronectin with HOCl or MPO/H₂O₂/Cl⁻ system in the presence of I⁻

Human plasma fibronectin (0.228 μM final concentration for SDS-PAGE and immunoblotting, 1.14 μM for HPLC analysis) was diluted in phosphate buffer (0.1 M final concentration, pH 7.4) containing Cl⁻ (0.1 M) and I⁻ over the concentration range 0.01–400 μM. For the MPO/H₂O₂ system, a 500-fold molar excess of H₂O₂ over the enzyme concentration, was added in five equal aliquots to samples containing 100 nM MPO over a period of 10 min and incubated for 2 h at 37 °C.

2.3. Ultra high-performance liquid chromatography (UPLC)

Loss of parent amino acids was quantified by UPLC analysis with pre-column derivatization using o-phthalaldehyde. Fibronectin
samples (25 μg of protein in 50 μl 0.1 M phosphate buffer) were hydrolysed using 4 M methanesulfonic acid as described previously [56], with minor modifications. Proteins were precipitated by the addition of 150 μl 10.67% (w/v) trichloroacetic acid and incubated at 4°C for 15 min. After removal of the supernatant, the protein pellet was hydrolysed by the addition of 50 μl 4 M MSA containing 0.2% (w/v) tryptamine (Sigma Aldrich) and incubation for 16 h under vacuum at 110°C. The samples were then neutralised with 55 μl freshly prepared 4 M NaOH, filtered using NanoSep MF 0.2 μm centrifugal filters and diluted 10-fold with 0.2 M aqueous sodium carbonate buffer, pH 10.3. Pre-column derivatization of the diluted samples (40 μL) was performed with OPA (40 μl, 1 mg mL⁻¹ in 0.2 M aqueous sodium carbonate buffer, pH 10.3, with 1 μL mL⁻¹ 2-mercaptoethanol added prior to derivatization). Standard curves were generated using commercially-available amino acid mixtures. The fluorescently tagged amino acid derivatives were separated on a Shimadzu Nexera system using a Kinetex 2.6 μm EVO C18 100 Å LC column (150 × 3.0 mm) and eluted using a gradient system (Buffer A: 100 mM sodium acetate, pH 5.3 in water with 2.5% (v/v) tetrahydrofuran and 15% (v/v) methanol; Buffer B: 100 mM sodium acetate pH 5.3 in water with 2.5% (v/v) tetrahydrofuran and 80% (v/v) methanol). A flow rate of 0.8 mL min⁻¹ was used, with the following gradient: 100% buffer A for 3 min, 10-10.5% buffer B linear gradient over 7.5 min, 10.5% buffer B for 5 min, 10.5-65% buffer B linear gradient over 3.5 min, 65-100% buffer B linear gradient over 1 min, 100% buffer B for 2 min, 100-0% buffer B linear gradient over 0.5 min, followed by equilibration at 100% buffer A for 3.5 min. The tagged amino acids were detected using a Shimadzu RF-20A fluorescence detector with λex 340 nm and λem 440 nm.

2.4. SDS-PAGE and immunoblotting

Samples for SDS-PAGE analysis were prepared using NuPAGE LDS Sample Buffer (4x dilution) and NuPAGE Sample Reducing Agent (10x dilution) according to the manufacturer’s instructions (Invitrogen). Protein samples were denatured by incubation at 70°C for 10 min. Proteins were loaded at 0.5 μg per well for 12-well gels, and 0.375 μg per well for 15-well gels. HiMark pre-stained protein standards (31–460 kDa) were used as molecular mass markers. Electrophoresis was carried out on 1 mm NuPAGE NOVEX 3–8% Tris-Acetate Gels using NuPAGE Tris-Acetate SDS Running Buffer at 150 V for 70 min. Following electrophoretic separation, proteins were analysed using immunoblotting.

For immunoblotting, proteins were electroblotted onto PVDF membranes over a period of 7 min using an iBlot* transfer apparatus (Invitrogen). The membranes were blocked with 1% (w/v) BSA in TBS with Tween 20 (TBST) for 1 h and then incubated with primary antibody (A17, 1:10,000 and anti-dityrosine, 1:500) in blocking solution overnight at 4°C. Membranes were then rinsed 3 times with TBST for 5 min before incubation with secondary HRP-conjugated antibody. Unbound antibody was removed by 4 washes with TBST for 10 min, and once with TBS for 10 min. Immune complexes were detected using Western Lightning Plus ECL reagent (NEL104001EA; Perkin Elmer, Waltham, MA, USA) and imaged using a G: BOX Chemi XR5 system (Syngene).

2.5. ELISA-based analysis of loss of parent fibroenin epitopes and HOCl-mediated protein damage

Human plasma fibroenin (50 μL per well, 5 μg mL⁻¹ in 0.1 M phosphate buffer, pH 7.4) was coated onto 96-well high-binding microtitre plates by incubation overnight at 4°C. The wells were then washed twice with 200 μL PBS to remove any excess or non-bound fibroenin, then treated with MPO (20 nM), H2O2 (32 μM), Cl⁻ (100 mM) and varying concentrations of I⁻ in a total volume of 50 μL. 0.1 M phosphate buffer, pH 7.4. After incubation at 37°C for 2 h, the wells were washed twice with 200 μL PBS and blocked with 100 μL 0.1% casein (w/v) in PBS for 1 h at 21°C. The wells were then washed twice with 200 μL PBS and incubated with 50 μL primary antibody (diluted in 0.1% casein (w/v) in PBS; A17 1:25,000, A32 1:2000, 2D10G9 1:100) overnight at 4°C. Unbound antibody was removed by two washes with 200 μL PBST, and the wells were then incubated with 50 μL secondary antibody (Alkaline Phosphatase conjugated anti-mouse Ig in 0.1% casein (w/v) in PBS; 1:1000) for 1 h at 21°C. Unbound secondary antibody was then removed by four washes with 200 μL TBST. TBST was employed for the final washes to avoid interference of phosphate in the Alkaline Phosphatase assay, in which 50 μL of Alkaline Phosphatase Yellow (p-nitrophenylphosphate, pNPP) substrate solution (Sigma Aldrich) was added to each well and the absorbance measured at 405 nm using a microplate reader (SpectraMax i3x Multi-Mode reader).

2.6. Determination of 3-chloro-L-tyrosine by LC-MS

Protein samples (25 μg) were precipitated with TCA (8% w/v final concentration) and spiked with isotope-labelled 3-chloro-[13C6]tyrosine (100 pmol) before evaporation using a centrifugal vacuum concentrator for 1 h at 60°C. The protein pellet was hydrolysed overnight in 4 M methanesulfonic acid (50 μL) under vacuum at 110°C. The resulting liberated amino acids were partially purified by solid-phase extraction using 1 mL C-18 cartridges (Supelco), with the columns activated using 100% methanol (1 mL), followed by equilibration with 0.1% TFA in water (2 × 1 mL). Samples were diluted with 1% TFA in water (10 μL hydrolysisate into 400 μL of 1% TFA) in order to improve ion-pairing and subsequent binding of amino acids to the C18 material. The samples were loaded onto the column and washed with 0.1% TFA in water (1 × 1 mL) followed by elution with 50% methanol containing 0.1% formic acid (1 × 1 mL). Extracts were dried at 60°C under vacuum for 4 h and then redissolved in 50 μL 0.1% formic acid. 3-Chlortyrosine (3-CTyr) was quantified by ESI LC-MS in the positive ion mode using a Bruker Impact HD II mass spectrometer. Samples were separated by gradient elution using a Phenomenex Aeric™ 2.6 μm PEPTIDE XB-C18 250 × 2.1 mm HPLC column. The elution was initiated at 3% B for 1 min, followed by gradient elution from 3 to 50% B over 9 min, 50–80% B over 2 min, followed by isocratic elution using 80% B for 3 min, before decreasing to 3% B over 2 min and re-equilibration at 3% B for 3 min. Buffer A consisted of 0.1% formic acid in H2O, and buffer B 80% acetonitrile in H2O with 0.1% formic acid. The electrospray needle was held at 4500 V, with end plate offset of 500 V and temperature of 200°C. Nitrogen gas was used for both the nebuliser (2.0 Bar) and as the dry gas (8.0 L min⁻¹). An external standard curve was generated for 3-CTyr with 78 fmol–20 pmol loaded onto the column, with the internal standard maintained at a loading of 4 pmol. A linear response of 3-CTyr relative to the internal standard was observed over this concentration range. Standards were prepared in 0.1% formic acid in H2O. Spectra were collected in MS1 mode and quantification performed on extracted ion chromatograms for 3-CTyr (m/z 216.04) and 3-chloro-[13C6]tyrosine (m/z 222.06).

2.7. Determination of H2O2 consumption by MPO

Consumption of H2O2 by MPO was determined in the presence of Cl⁻ and varying amounts of I⁻ using an H2O2-sensitive electrode (World Precision Instruments, HPO-ISO-2), as reported previously [38]. Solutions were prepared using 0.1 M sodium phosphate buffer, pH 7.4, with 50 μM H2O2 added, followed by 20 nM MPO. Methionine (250 μM) was included to quench the HOCl formed and prevent loss of enzyme activity. The removal of H2O2 was monitored until complete consumption. The rate of turnover was determined by using the initial linear sections of the H2O2 consumption curves, over a period of 120 s, after stabilization of the signal following MPO injection.
2.8. Cell adhesion centrifugation assay

Human plasma fibronectin (50 μL per well, 10 μg mL⁻¹ in 0.1 M phosphate buffer at pH 7.4) was coated onto a 96-well tissue-culture treated, clear-bottom, black well plates by incubation overnight at 4 °C. The wells were washed twice with 200 μL PBS to remove excess or non-bound fibronectin, then treated with MPO (20 nM), H₂O₂ (64 μM), Cl⁻ (100 mM) and varying concentrations of I⁻ in a total volume of 50 μL. 0.1 M phosphate buffer, pH 7.4. Following incubation at 37 °C for 2 h, the wells were washed twice with 200 μL DPBS and blocked for 30 min at 21 °C with 100 μL BSA in DPBS (1% w/v, heat-denatured at 85 °C for 12 min, sterile-filtered). The wells were then washed twice with 200 μL DPBS to remove blocking solution, and human coronary artery endothelial cells added (Cell Applications, San Diego, CA, USA; 20,000 cells well⁻¹ in 50 μL basal media, pre-loaded with Calcein-AM (with Mg²⁺/Ca²⁺), sealed with adhesive foil and placed upside down in a centrifuge. The plate was centrifuged at 40 g for 5 min followed by removal of the supernatant containing unbound cells by inversion of the plate. Relative cell density was obtained by measurement of Calcein-AM fluorescence (λem 485 nm, λex 490 nm, 1 cm λ, taurine (40 mM) was incubated at 37 °C, further to investigation of the effects of I⁻ upon MPO-mediated changes in protein structure, fibronectin (1 μM) was treated with MPO (0.1 μM)/H₂O₂ (500 μM)/Cl⁻ (100 mM) in the absence or presence of varying concentrations of I⁻ (0–400 μM). Effects on fibronectin structure were probed by SDS-PAGE followed by immunoblotting. In the presence of MPO/H₂O₂/Cl⁻, additional bands were detected by immunoblotting using mAb A17, at masses higher and lower that the parent protein mass [58,59]. The formation of modifications to functional epitopes on the protein.

In the absence of I⁻, a significant loss of epitope recognition of both the cell binding region (mAb A17, 38.3 ± 5.6% loss versus control) and heparin binding region (mAb A32, 50.3 ± 9.0% loss versus control) was observed after exposure of the fibronectin to the MPO/Cl⁻/H₂O₂ system. The presence of increasing concentrations of I⁻ resulted in a decreased loss of epitope recognition to levels of ca. 90% for both antibodies, with this being statistically significant for 1–100 μM I⁻. The small decrease in antibody recognition at very high I⁻ concentrations (50–100 μM) was not statistically significant.

The formation of modified epitopes on fibronectin was probed with mAb 2D10G9 which recognises HOCl-modified proteins [25,26,60–62]. Untreated fibronectin, BSA and HAS (used as controls) showed only very low background signals. After exposure to the MPO/Cl⁻/H₂O₂ system, the oxidant-treated samples showed significant recognition by 2D10G9, consistent with significant HOCl-mediated damage (Fig. 1C). The presence of increasing concentrations of I⁻ resulted in decreased recognition by 2D10G9, consistent with lower extents of damage, with this being significant at I⁻ concentrations > 1 μM. Whilst 2D10G9 also recognise HOBr-induced damage [34], the current results suggest that this antibody does not recognise HOI-mediated protein damage, though the exact epitope recognised by this antibody is poorly defined [25,34].

3. Results

3.1. I⁻ protects against damage to functional regions of human fibronectin induced by MPO/Cl⁻/H₂O₂

Exposure of human fibronectin to increasing concentrations of HOCl has been shown previously to result in chlorination of tyrosine (Tyr) residues and oxidation at cysteine (Cys), methionine (Met) and tryptophan (Trp) residues [58,59]. The effect of I⁻ on these modifications was therefore examined in reaction systems in which human plasma fibronectin (0.228 μM) was exposed to MPO (100 nM)/H₂O₂ (50 μM)/Cl⁻ (100 mM) using a microplate-based ELISA method to examine alterations to functional epitopes on the protein.

In order to investigate the effect of I⁻ upon MPO-mediated changes in protein structure, fibronectin (1 μM) was treated with MPO (0.1 μM)/H₂O₂ (500 μM)/Cl⁻ (100 mM) in the absence or presence of varying concentrations of I⁻ (0–400 μM). Effects on fibronectin structure were probed by SDS-PAGE followed by immunoblotting. In the presence of MPO/H₂O₂/Cl⁻, additional bands were detected by immunoblotting using mAb A17, at masses higher and lower that the parent protein fibronectin, which appears as a single broad band due to the similarity in masses of the two (α and β) chains under reducing conditions (c.f. lanes 1 vs. 12 in Fig. 2). The presence of low concentrations of I⁻ resulted in decreased recognition by 2D10G9, consistent with lower extents of damage, with this being significant at I⁻ concentrations > 1 μM. Whilst 2D10G9 also recognise HOBr-induced damage [34], the current results suggest that this antibody does not recognise HOI-mediated protein damage, though the exact epitope recognised by this antibody is poorly defined [25,34].
Fig. 1. ELISA based detection of HOCl-mediated damage to human plasma fibronectin incubated with a MPO/H$_2$O$_2$/Cl$^-$ system, in the absence or presence of I$^-$. Antibodies were used to detect (A) damage to the cell-binding fragment (anti-fibronectin mAb A17), (B) damage to the heparin-binding region (anti-fibronectin mAb A32), and (C) HOCl-induced damage (mAb 2D10G9, raised against HOCl-modified protein). Human plasma fibronectin (2.5 μg in 50 μL) was treated with MPO (20 nM), H$_2$O$_2$ (32 μM), Cl$^-$ (100 mM) for 2 h at 37 °C in 0.1 M phosphate buffer, pH 7.4. Data are presented as mean ± SD from 3 independent experiments. Insignificant statistical significance of the control against the oxidized sample in the absence of I$^-$ (0 μM I$^-$) as determined by Student’s t-test. * Indicates statistical significance against the oxidized sample in the absence of I$^-$ (0 μM I$^-$), as determined by one-way ANOVA with post-hoc analysis using Dunnett’s multiple comparison test.
3.3. Quantification of amino acid oxidation and 3-chlorotyrosine formation on fibronectin induced by MPO/Cl\(^{-}\)/H\(_2\)O\(_2\) in the presence of varying concentrations of I\(^{-}\)

The effect of increasing I\(^{-}\) concentrations on MPO-mediated oxidation of amino acids present on fibronectin was investigated using UPLC analysis of hydrolysed fibronectin samples. Fibronectin (25 μg in 50 μL 0.1 M phosphate buffer) was incubated with MPO/Cl\(^{-}\)/H\(_2\)O\(_2\) (as described above) in the absence and presence of varying concentrations of I\(^{-}\), prior to total amino acid analysis. In the absence of I\(^{-}\), the levels of Met and Trp were decreased, relative to the untreated protein, on exposure to MPO/Cl\(^{-}\)/H\(_2\)O\(_2\). All other amino acid residues examined were not significantly affected. In the presence of increasing levels of I\(^{-}\) the loss of Met was decreased in a dose-dependent manner, with this being statistically significant at > 10 μM I\(^{-}\) (Fig. 3). No significant change was detected for Trp, though a trend towards a decreased loss was apparent (Fig. 3). While no significant loss of Tyr was detected with MPO/Cl\(^{-}\)/H\(_2\)O\(_2\) in the absence of I\(^{-}\), the presence of high concentrations of this ion (200–400 μM) resulted in a statistically-significant decrease of this amino acid.

We have recently shown that human plasma fibronectin is readily modified by MPO-derived HOCl and results in significant chlorination of the protein at Tyr residues, giving both 3-chloroTyr (3-ClTyr) and 3,5-dichloroTyr [58]. Consequently the absolute concentrations of 3-ClTyr formed on both fibronectin and BSA (as a positive control and for comparison with previous data) were determined in both the absence and presence of increasing I\(^{-}\) concentrations, using LC-MS. The levels of 3-ClTyr were markedly elevated on both proteins compared with MPO/Cl\(^{-}\)/H\(_2\)O\(_2\) in the absence of I\(^{-}\), with the levels detected on BSA (ca. 450 nM, 6.5 nmol mg\(^{-1}\) protein) consistent with previous data [44,63]. Higher levels were detected on fibronectin (ca. 3 μM, 31 nmol mg\(^{-1}\) protein). The presence of I\(^{-}\) in both the fibronectin and BSA systems decreased 3-ClTyr levels in a dose-dependent manner, with the decrease statistically-significant at ≥ 10 μM I\(^{-}\) (Fig. 4). These data are consistent with the mAb 2D10G9 antibody studies (Fig. 1C).

3.4. I\(^{-}\) improves adhesion of human coronary artery endothelial cells (HCAECs) to oxidized fibronectin in the MPO/Cl\(^{-}\)/H\(_2\)O\(_2\) system

Previous data indicate that human coronary artery endothelial cells (HCAEC) adhere less well to HOCl-modified fibronectin when compared to native fibronectin, and also have altered gene expression in response to the modified protein [59]. Consequently, cell adhesion assays were performed to test whether the presence of I\(^{-}\) in the MPO/Cl\(^{-}\)/H\(_2\)O\(_2\) system could decrease the loss of cell adhesion arising from HOCl-induced modification. Treatment of fibronectin with the MPO/Cl\(^{-}\)/H\(_2\)O\(_2\) system in the absence of I\(^{-}\) resulted in decreased HCAEC adhesion (60 ± 1.9% relative to non-oxidized control). The presence of low concentrations of I\(^{-}\) decreased this loss of function in a dose-dependent manner, with this being statistically significant at ≥ 1 μM (Fig. 5).

3.5. Myeloperoxidase activity is perturbed by high concentrations of I\(^{-}\)

The data presented above indicate that I\(^{-}\) at low concentrations can reduce the extent of damage induced by MPO/H\(_2\)O\(_2)/Cl\(^{-}\) reaction systems. One potential rationale for these effects is potential (reversible or irreversible) inhibition of the MPO catalytic cycle, or by other secondary reactions involving I\(^{-}\). In order to test these possibilities, the catalytic turnover of MPO was quantified, as measured by H\(_2\)O\(_2\) consumption (using a H\(_2\)O\(_2\)-sensitive electrode) in the presence of Cl\(^{-}\) (100 mM), Met (250 μM, as a scavenger for HOCl to prevent enzyme auto-inactivation), and the absence and presence of increasing concentrations of I\(^{-}\). H\(_2\)O\(_2\) (50 μM) was introduced into a phosphate-buffered solution containing Cl\(^{-}\) (100 mM) and I\(^{-}\) (0, 1, 10, 25, 100 μM), and the reaction initiated by the addition of MPO (20 nM). Under these conditions the formation of Compound I, by reaction of the native enzyme with the added H\(_2\)O\(_2\) is rapid, and the turnover of the enzyme is limited by the reaction of Compound I with Cl\(^{-}\) or I\(^{-}\). No direct reaction between H\(_2\)O\(_2\) and I\(^{-}\) was observed prior to the addition of MPO. In the absence of I\(^{-}\), H\(_2\)O\(_2\) was consumed at a rate of 3.5 μM min\(^{-1}\)
Fig. 3. UPLC quantification of (A) Met, (B) Trp, (C) Tyr and (D) Phe on human plasma fibronectin (5.68 μM) following treatment with MPO/H2O2/Cl− in the absence or presence of I−. Human plasma fibronectin (25 μg in 50 μL, 1.14 μM) was treated with MPO (100 nM), H2O2 (500x excess, 570 μM), Cl− (100 mM) in the absence or presence of increasing I− (0–400 μM) for 2 h at 37 °C in 0.1 M phosphate buffer, pH 7.4. Data are presented as mean + SD of three independent experiments. # Indicates statistical significance of the control against the oxidized sample in the absence of I− (0 μM I−) as determined by Student’s t-test. * Indicates statistical significance against the oxidized sample in the absence of I− (0 μM I−) as determined by one-way ANOVA with post-hoc analysis using Dunnett’s multiple comparison test.

Fig. 4. Quantification of 3-ClTyr on (A) BSA, and (B) human plasma fibronectin, following treatment with MPO/H2O2/Cl− in the presence of I−. BSA or human plasma fibronectin (25 μg in 50 μL, 1.14 μM) were incubated with MPO (100 nM), H2O2 (500x excess, 570 μM), Cl− (100 mM) in the absence or presence of increasing concentrations of I− (0–400 μM) for 2 h at 37 °C in 0.1 M phosphate buffer, pH 7.4, before analysis by LC-MS. Data are presented as mean + SD from three independent experiments. # Indicates statistical significance of the control against the oxidized sample in the absence of I− (0 μM I−) as determined by Student’s t-test. * Indicates statistical significance against the oxidized sample in the absence of I− (0 μM I−) as determined by one-way ANOVA with post-hoc analysis using Dunnett’s multiple comparison test.
Reactions were performed at 25 °C. Panel (A) shows representative time course data (from 3 independent experiments) for H2O2 consumption. Panel (B) shows removed by centrifugation at 40 °C in 0.1 M phosphate buffer at pH 7.4. Wells were washed with DPBS and blocked with 1% denatured-BSA in DPBS. HCAECs pre-stained with Calcein-AM were coated onto a MPO/H2O2/Cl− system in the absence or presence of I−. Human plasma fibronectin (2.5 μg in 50 μL) was coated onto a 96-well plate and treated with MPO (20 nM), H2O2 (32 μM), Cl− (100 mM) for 2 h at 37 °C in 0.1 M phosphate buffer, pH 7.4. Wells were washed with DPBS and blocked with 1% denatured-BSA in DPBS. HCAECs pre-stained with Calcein-AM (5 μM) were added and allowed to adhere for 2 h. Non-adherent cells were then removed by centrifugation at 40g for 5 min. Adherent cells were subsequently quantified by fluorescence of the Calcein-AM dye as described in the Materials and methods. Data are presented as mean + SD from three independent experiments. # Indicates statistical significance of the control against the oxidized sample in the absence of I− (0 μM I−) as determined by Student’s t-test. * Indicates statistical significance against the oxidized sample in the absence of I− (0 μM I−) as determined by one-way ANOVA with post-hoc analysis using Dunnett’s multiple comparison test.

(Fig. 6) The presence of low concentrations of I− did not significantly perturb this rate, with only concentrations of I− ≥ 25 μM, found to significantly enhance the turnover of MPO, with consumption rates of 5.7 and 7.5 μM min−1 detected at 25 and 100 μM respectively (Fig. 6).

3.6. Determination of iodate (IO3−) formation by the MPO/Cl−/H2O2 system

As MPO does not appear to be significantly inhibited by low concentrations of I−, the potential formation of iodate (IO3−), a known oxidation product of I−, was examined and quantified, as well as the potential perturbation of MPO activity by this species. Previous studies have postulated that reaction of I− with either the MPO/H2O2/Cl− system, or its product HOCl, forms HOI and hence IO3− via a rapid disproportionation reaction that regenerates a proportion of the I− originally consumed (Equation (2)) [64]. These secondary products, such as IO3−, would be expected to be less reactive than HOI itself [65]. The formation of IO3− on reaction of HOCl with I− was confirmed by spectrophotometric assay after reaction of HOCl (100 μM) with equimolar concentrations of I− at 21 °C over a period of 20 min (Table 1). Under these conditions HOCl should be converted rapidly to HOI which will undergo moderately slow (quantitative) disproportionation to I− and IO3− (Equations (1) and (2)) [64,66]. The concentration of IO3− detected was ca. 33 μM, consistent with the expected value of 33 μM predicted from this chemistry. IO3− generation was also examined after incubation of MPO with H2O2 (100 μM), Cl− (100 mM) and I− (100 μM) at 37 °C over a period of 2 h. The concentration of IO3− detected was below the limit of detection of the assay (2 μM) in both the absence and presence of 50 nM BSA (as a potential target for IO3−). Subsequent bolus addition of HOCl (100 μM) to these reactions, to oxidize any residual I−, resulted in the detection of ca. 34 μM IO3− in both the absence and presence of BSA (Table 1). These data suggest that most of the initial I− is not converted

Table 1

<table>
<thead>
<tr>
<th>Oxidation system</th>
<th>Concentration of IO3− detected/μM</th>
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<tbody>
<tr>
<td>I− alone</td>
<td>− BSA</td>
</tr>
<tr>
<td>MPO + H2O2 + I− + Cl−</td>
<td>− BSA + BSA</td>
</tr>
<tr>
<td>− HOCl</td>
<td>&lt; 2 (LOD)</td>
</tr>
<tr>
<td>+ HOCl</td>
<td>33.0 ± 0.6 *</td>
</tr>
<tr>
<td></td>
<td>33.7 ± 0.2</td>
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<td>33.7 ± 0.5</td>
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Fig. 6. Consumption of H2O2 over time detected using a H2O2-sensitive electrode (HPO-ISO-2) in the absence and presence of the MPO system in the absence or presence of the indicated concentrations of I−. MPO (20 nM) was spiked into a solution of Cl− (100 mM) and H2O2 (50 μM) in 0.1 M sodium phosphate buffer at pH 7.4. Reactions were performed at 25 °C. Panel (A) shows representative time course data (from 3 independent experiments) for H2O2 consumption. Panel (B) shows the rate of H2O2 consumption as determined by the slope of the curve over the first 120 s following stabilization of the signal after injection of MPO. Data in panel (B) are presented as mean ± SD from 3 independent experiments, with * indicating statistical significance against the oxidized sample in the absence of I− (0 μM I−) as determined by one-way ANOVA with post-hoc analysis using Dunnett’s multiple comparison test.
to IO₃⁻, or other products, during incubation with MPO/H₂O₂/Cl⁻.

As IO₃⁻, even if formed at low levels, might act as an MPO inhibitor, the activity of MPO was examined by determining the yield of chloramines formed from added taurine, by HOCl, using the TNB assay [56]. The yield of taurine chloramines was not perturbed by the presence of IO₃⁻, at concentrations up to 40 μM, indicating that IO₃⁻ is not a significant inhibitor of MPO activity (Fig. 7).

4. Discussion

Multiple studies have demonstrated an association between MPO levels and outcomes of cardiovascular disease, with high levels indicative of poor health outcomes [67]. Previous work has shown that SCN⁻ can reduce the extent of MPO-induced damage on BSA and human plasma proteins, as judged by Met oxidation and 3-ClTyr formation [44]. Other studies have also shown that damage to fibronectin can be attenuated by SCN⁻ [13], and that this anion can prevent damage in animal models of disease including cystic fibrosis and atherosclerosis [45, 68, 69]. Here we have examined whether I⁻, another high affinity substrate for MPO, behaves in a similar manner, as I⁻ levels can be readily elevated in animals and humans by simple interventions. Such an activity might therefore have significant health benefits, and be readily applied.

Exposure of plasma fibronectin to HOCl and MPO/H₂O₂/Cl⁻ induces protein damage in a dose-dependent manner [58, 59]. The residues modified by such exposure have been characterized by UPLC and MS peptide mass mapping, and include Tyr, Trp, His, Met and Cys/cysteine [58]. Some of these modifications occur within functional (cell- and heparin-binding) domains, consistent with the loss of native epitopes, and altered functional properties including its capacity to act as a substrate for cell adherence and proliferation [58, 59].

In the current study it has been demonstrated that such damage can be ameliorated by I⁻ at concentrations as low as 1 μM, with these low concentrations providing protection against modification to both the cell-binding and heparin-binding domains (Fig. 1A and B). Furthermore, the loss of cell adhesion to fibronectin induced by MPO/H₂O₂/Cl⁻ was also attenuated by low concentrations of I⁻ (Fig. 3).

Previous studies have shown that HOCl can modify the structure of fibronectin [59], with dose-dependent aggregation and fragmentation detected by SDS-PAGE with silver staining, and use of mAb A17 against the cell-binding epitope. In contrast, the data presented here indicate that the species formed by the MPO/H₂O₂/Cl⁻ system in the presence of I⁻, did not give rise to marked cross-linking or fragmentation of the protein, except at extremely high concentrations of I⁻. Under the latter conditions significant smearing of the protein bands was detected to both lower and higher molecular masses, with the latter being particularly marked. These data indicate that HOI, the likely initial product of I⁻ oxidation, does not induce dramatic effects on the protein structure when formed at modest concentrations. In contrast, molecular iodine (I₂) or I₃⁻, which may be formed from I⁻ by HOCl at high concentrations, may be the source of these changes, with this occurring via iodonation of Tyr (and possibly other residues) and cross-linking (possibly di-Tyr formation) (cf. the reactions of thyroid peroxidase) [70, 71]. There is no evidence for the presence of such high I⁻ concentrations ( > 100 μM; Fig. 2) at sites in inflammation, though they may occur in extreme cases of I⁻ overdoses. Even in the thyroid gland, where I⁻ is concentrated (to levels 20–50 times higher than those of plasma [72, 73]) and used by thyroid peroxidase to iodinate thyroglobulin [70], these levels are below these that induce marked fibronectin damage.

Amino acids represent a major target for HOCl [74]. Under our conditions, most of the amino acids present in fibronectin were unaffected by the MPO/H₂O₂/Cl⁻ system, both in the absence and presence of I⁻. The data obtained in the absence of I⁻ are in accord with previous reports for HOCl and MPO/H₂O₂/Cl⁻, with stable (long-lived) modifications limited to Met, Cys/cystine, Trp, Tyr and His [58, 59]. Reaction at amines, such as the ε-amino group of Lys side-chains, occurs at modest rates, but this yields unstable chloramines (RNHCl) [75], which would not be detected under the conditions used in these analyses. In the current study, oxidation of Met by the MPO/H₂O₂/Cl⁻ system was decreased in a dose-dependent manner by I⁻. In contrast to previous and current MS studies (see above and below), no significant loss of Tyr was detected by UPLC, probably due to the insensitivity of this method at low levels of modification. However a small but significant loss of Tyr was detected by UPLC with the MPO/H₂O₂/Cl⁻ system with high I⁻ concentrations in agreement with previous data on the iodination of Tyr residues by peroxidases (Fig. 4A) [70].

The MS analyses showed significant formation of 3-CTyr induced by MPO/H₂O₂/Cl⁻ on both fibronectin and the model protein BSA, with the levels of this biomarker decreased in a dose-dependent manner by increasing I⁻ concentrations. HOCl-mediated damage recognised by the mAb 2D10G9 (raised against HOCl-damaged low-density lipoproteins) was also significantly reduced in the presence of I⁻, as determined by ELISA assay. As previous studies have shown that 3-CTyr levels correlate with the severity of chronic kidney damage and cardiovascular disease [76], modulation of the formation of this biomarker may be of clinical significance.

Fibronectin and MPO have been shown previously to colocalise in diseased tissue [59], and MPO has also been shown to colocalise with HOCl-modified proteins in atherosclerotic plaques [34, 77]. Furthermore, proteins immunoprecipitated with mAb 2D10G9 (i.e. species damaged by HOCl) have been shown to be recognised by fibronectin antibodies and to migrate on gels at the expected masses for fibronectin chains, consistent with fibronectin modification by MPO/H₂O₂/Cl⁻ in human atherosclerotic lesions [59]. Increased I⁻ levels in vivo may therefore reduce the amount of tissue damage induced by MPO. These results provide a novel mechanism which rationalizes the improved outcomes observed in animals (mice, rats and pigs) administered I⁻ prior to induction of an acute myocardial infarction [50, 78].

While I⁻ is a high affinity substrate for MPO, the mechanism through which I⁻ reduces damage to fibronectin (and also BSA) is yet to be fully elucidated. Although the rate constants for reaction of Cl⁻ with Compound I of MPO is much lower than that for I⁻, the high plasma concentrations of Cl⁻ would be expected to more than compensate for this, and hence with normal physiologic anion concentrations, Cl⁻ would be expected to outcompete I⁻ as a substrate [7]. In the case of SCN⁻, the rate constants for reaction of this anion and I⁻ with
Compound I are similar, and therefore the higher concentrations of SCN$^-$ compared to I in plasma, would also be expected to limit I$^-$ oxidation. These data therefore suggest that competitive reaction of I$^-$ with Compound I may not be the sole factor responsible for the decreased damage observed with increasing I$^-$ concentrations, assuming the published rate constants for reactions of Compound I are correct.

A second potential explanation for the observed reduction in damage is via direct oxidation of I$^-$ with HOCl, with consequent consumption of the latter (Equation (1)). This reaction is rapid [66] and hence should compete with protein targets for HOCl (cf. k for reaction with Cys of $3 \times 10^6 \text{M}^{-1}\text{s}^{-1}$) [79]. However, the data reported here indicate that statistically-significant protection occurs with I$^-$ concentrations that considerably below the concentrations of HOCl that are likely to be formed from the H$_2$O$_2$ provided to MPO. Under such conditions, I$^-$ would only be expected to remove a limited amount of the HOCl formed, assuming that the stoichiometry of Equations (1) and (2) is correct. Thus, each mole of I$^-$ would be expected to quench 3 mol of HOCl. Whilst conversion of HOI to IO$_3^-$, which is a far weaker oxidant than either H$_2$O$_2$, HOCl or HOI, might partially account for the substoichiometric effects, the iodate assay data (Table 1) indicates that little IO$_3^-$ is formed on reaction of MPO/H$_2$O$_2$/Cl$^-$/I$^-$, and the spiking experiments with added HOCl (to convert remaining I$^-$ to HOI and therefore IO$_3^-$) reveal that I$^-$ is still present at high concentrations and is not converted to HOI or IO$_3^-$. Reactions with BSA provided similar data, indicating there is no significant consumption of I$^-$ by the protein. IO$_3^-$ also had no effect on chloramine formation (a marker of enzyme activity), consistent with recent observations that, in contrast to I$^-$, IO$_3^-$ does not provide a benefit in a mouse model of reperfusion injury [50]. Our results (Fig. 7) imply that IO$_3^-$, even if formed transiently, does not have a significant inhibitory effect on MPO. These data indicate that direct scavenging of HOCl by I$^-$ is unlikely to be the major damaging-limiting pathways, unless other, unknown, recycling reactions occur.

Potential inhibition of MPO activity by I$^-$ also does not appear to be a major process as the concentrations of I$^-$ that provide protection to fibronectin did not significantly perturb H$_2$O$_2$ consumption by MPO. These data therefore suggest that I$^-$ does not directly inhibit MPO (e.g. by binding to and/or blocking the active site). These studies also indicate that direct oxidation of I$^-$ by H$_2$O$_2$ is not a significant event, as no loss of H$_2$O$_2$ was observed upon addition of I$^-$ in the absence of MPO; this is consistent with a slow reaction between these materials at the concentrations used here (Fig. 6A) and also previous data [80].

Interference with the catalytic cycle of MPO, and particularly removal of Compound I via conversion to Compound II via a one-electron (peroxidase cycle) reaction also appears unlikely, as although I$^-$ has a modest one-electron reduction potential (1/1’, +1.35 V), this value is greater than that the one-electron reduction potential of Compound I (+1.16 V) and hence thermodynamically unfavourable [6,81].

These arguments suggest that, rather than inhibiting the enzyme or acting as a competitive substrate, I$^-$ act in a catalytic manner, via an unidentified very fast secondary reaction mechanism. Alternatively, it may be a more efficient substrate for the enzyme than previously indicated [7]. The precise mechanism giving rise to the observed protection by low micromolar concentrations of I$^-$ therefore warrants additional study.

Irrespective of the precise mechanism, the data presented here indicate that I$^-$ can reduce MPO-induced damage in vitro at concentrations that can be achieved physiologically, with amelioration of protein damage and loss of cell adhesion detected at I$^-$ concentrations as low as 1 μM. This concentration can be readily achieved in humans by oral supplementation [53], and it is also possible that local in vivo concentrations of I$^-$ may be higher than systemic values, and may therefore result in greater effects than previously suspected. These results indicate the need for further investigation of I$^-$ as a therapeutic agent and, more specifically, whether the observed benefits of I$^-$ supplementation in cardiovascular disease are a result of interactions with MPO and its oxidants.

Conflicts of interest

The authors declare no conflicts of interest with regard to the data presented.

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References


D.F. Gardner, R.M. Center, R.D. Ugter, Effects of low dose oral iodide supplemen-


S. Vanschiltegrunng, C.Y. Chuang, L.C. Hawkins, A. Hammer, G. Hoefler, E. Malle, M.J. Davies, Oxidation of human plasma ﬂumin by myeloperoxidase-de-


J. Talib, D.I. Pattison, J.A. Harmer, D.S. Celermajer, M.J. Davies, High plasma thiocyanate levels are associated with enhanced myelo-

J. Arnhold, E. Monzani, P.G. Furtmüller, M. Zederbauer, L. Casella, C. Obinger,


