Research paper

11β-Hydroxysteroid dehydrogenase type 1 contributes to the regulation of 7-oxysterol levels in the arterial wall through the inter-conversion of 7-ketocholesterol and 7β-hydroxycholesterol

Tijana Mitić, Ruth Andrew, Brian R. Walker, Patrick W.F. Hadoke

Endocrinology Unit, University/BHF Centre for Cardiovascular Science, College of Medicine and Veterinary Medicine, University of Edinburgh, The Queen’s Medical Research Institute, Edinburgh EH16 4TJ, Scotland, UK

1. Introduction

Pro-atherogenic 7-oxysterols form a large component (40%) of oxidized LDL (oxLDL), of which 7-ketocholesterol (7-KC) contributes ~30% [1]. 7-KC is toxic to cells in the vessel wall, and can impair arterial function ex vivo [2]. Indeed, 7-KC and its metabolite 7β-hydroxycholesterol (7βOHC) inhibited endothelium-dependent, acetylcholine-induced relaxation of rabbit aortic rings in vitro [2]. In human umbilical vein endothelial cells (HUVECs), 7βOHC and 7-KC reduced the histamine-activated release of nitric oxide [3]. This inhibition of endothelial function by 7-oxysterols appears to be independent of their cytotoxic effects [4], but its mechanism is unclear. Importantly, 7-KC and 7βOHC differ in their proatherogenic potential, with 7-KC implicated as the major pro-inflammatory and cytotoxic oxysterol [5]. However, any differences between the functional effects of 7-KC and 7βOHC in the vasculature have not been addressed.

The balance between 7-KC and 7βOHC in tissues may be actively modulated. Recently, a novel route of metabolism of 7-oxysterols has been described, involving the enzyme 11β-hydroxysteroid dehydrogenase (11β-HSD) type 1. The primary role of 11β-HSD1 is to catalyse the pre-receptor generation of glucocorticoids, allowing tissue-specific amplification of glucocorticoid receptor activation.
Inactivation of glucocorticoids is catalysed by the type 2 isozyme of 11β-HSD (11β-HSD2) [7]. It is becoming increasingly apparent that 7-oxysterols are alternative substrates for 11β-HSD1 [8,9], and inhibition of the enzyme can result in accumulation of 7-KC [10]. Since both isozymes of 11β-HSD are present in the arterial wall [11–14], where they are able to inter-convert glucocorticoids [15], it is conceivable that inter-conversion of 7-oxysterols by these enzymes has a role in modulating vascular function.

We used mice with targeted disruption of the 11β-HSD1 gene (Hsd11b1) to investigate the hypothesis that 11β-HSD1 metabolises 7-oxysterols in the arterial wall, thus influencing 7-KC- and 7βOHC-mediated modulation of arterial function.

2. Methods

2.1. Chemicals and stock solutions

All solvents were HPLC grade (Fisher, Hemel Hempstead, UK) and were prepared containing an anti-oxidant (0.01% w/v butylated hydroxytoluene (BHT)) to prevent oxidative degradation of the lipids [3]. Steroids and oxysterols were from Steraloids (Newport, Rhode Island, USA); derivatization reagents from Fluka (Buchs, Switzerland), tissue culture reagents from Lonza (Reading, UK) and other chemicals from Sigma-Aldrich (Poole, Dorset, UK). Deuterium-labelled internal standards for GCMS were obtained from CDN Isotopes (Qmx Laboratories, Essex, UK). Stock solutions (30 mg/ml in ethanol with 250 μg/ml BHT) of 7-KC, 7βOH and 7αOH (an optical isomer of 7βOH) were freshly prepared as required. All steroids were prepared in 100% ethanol. Working solutions for tissue culture were prepared in standard Dulbecco’s modified Eagle’s medium (DMEM). Working solutions (25 μM 7-KC; 20 μM 7βOH) for microscopy were prepared by diluting the appropriate stock solution in DMEM without L-Arginine (Arg) or phenol red, but containing 1% charcoal-stripped foetal calf serum. These were the maximum concentrations of 7-oxysterols that could be achieved without sample precipitation. The final concentration of vehicle (ethanol with 250 μg/ml BHT) was <0.2%.

2.2. Animals

Male mice (age 8–16 weeks) homozygous for disrupted alleles of 11β-HSD1 (Hsd11b1−/−) [16] or 11β-HSD2 (Hsd11b2−/−) [7], on a C57Bl6/J background [12] were bred in-house. Controls were age- and sex-matched C57Bl6/J mice bred in-house. Mice were bred in-house. Controls were age-matched C57Bl6/J mice bred in-house [7,16]. Inactivation of glucocorticoids is catalysed by the type 2 isozyme of 11β-HSD2 [7]. It is becoming increasingly evident that both 7α-HSD and 7β-HSD are present in the arterial wall, thus in 7-oxysterol metabolism [14]. After the vessels had been equilibrated at their optimum resting force they were contracted with KCl (125 mM, 3 times) to induce maximal tension. Relaxations were expressed as a percentage of the contraction in log scale (pmol/mg/day). Medium was removed and deuterium-labelled (3H, d7) internal standards (IS) were added (50 μl) and lipids were extracted into chloroform/methanol (2:1, 8 ml) [21,22]. Samples were purified using Bond Elute Diol columns (100 mg, 1 ml; Varian, UK) and hydrolysed following mild saponification [24,25]. Oxidized lipids and cholesterol were extracted from neutralized samples (0.35 ml, 20% acetic acid) into diethyl ether (4 ml, 0.01% BHT) and evaporated to dryness under argon. Total cholesterol and 7-oxysterol concentrations were measured by GCMS and corrected for aortic protein levels.

2.4. Determination of plasma and aortic levels of 7-oxysterols and cholesterol

Concentrations of cholesterol and 7-oxysterols in the plasma and aortae were quantified by GCMS. Aortae from Hsd11b1−/− or C57Bl6/J mice were pooled from two animals, washed in PBS containing EDTA (0.5 mM), crushed under liquid nitrogen and homogenized. Protein concentration was determined using Bradford assay (Biorad, UK). Deuterium-labelled ([3H], d7) internal standards (IS) were added (50 μl) and lipids were extracted into chloroform/methanol (2:1, 8 ml) [21,22]. Samples were purified using Bond Elute Diol columns (100 mg, 1 ml; Varian, UK) [23] and hydrolysed following mild saponification [24,25]. Oxidized lipids and cholesterol were extracted from neutralized samples (0.35 ml, 20% acetic acid) into diethyl ether (4 ml, 0.01% BHT) and evaporated to dryness under argon. Total cholesterol and 7-oxysterol concentrations were measured by GCMS and corrected for aortic protein levels.

2.5. Metabolism of 7-oxysterols by 11β-HSD1 and 11β-HSD2 in vitro

2.5.1. In the mouse aorta

Rings (2 mm long) of aortae from C57Bl/J and Hsd11b1−/− mice (n = 8/group) were placed in a 24 well plate (1/well, in duplicate) and immersed in 1 ml DMEM (without L-Arg) containing 7-KC (25 μM), 7βOH (20 μM), 7αOH (20 μM) or vehicle (ethanol, with 50 μg/ml BHT) for 4 h (2 rings/treatment/mouse). The incubating medium was replaced every 60 min. After 4 h cumulative concentration–response curves were obtained for 5-hydroxytryptamine (5-HT; 1 × 10−9–1 × 10−4 M) and noradrenaline (NA; 1 × 10−9–1 × 10−4 M). In addition, cumulative concentration–response curves were obtained for the vasodilators, acetylcholine (ACh; 1 × 10−9–1 × 10−4 M, endothelium-dependent) and sodium nitroprusside (SNP; 1 × 10−5–1 × 10−4 M, endothelium-independent), following contraction with a sub-maximal concentration of 5-HT (3 × 10−2–1 × 10−5 M). Contractile responses are expressed as force per unit length (mN/mm).

Relaxations were expressed as a percentage of the contraction in response to the EC50 of 5-HT (% 5-HT).

For extended exposures [14], aortic rings were placed in a 24 well plate and immersed in 1 ml DMEM (without L-Arg) containing either 7-KC (25 μM), 7βOHC (20 μM), or vehicle (ethanol with 50 μg/ml BHT) and incubated overnight in a humidified incubator (37°C; 5% CO2). These vessels were then mounted in a myograph and functional studies performed, as described above, in the continued presence of the appropriate 7-oxysterol or vehicle.

2.5.2. Metabolism of 7-oxysterols in isolated mouse aortic rings

Thoracic aortae were isolated from male C57Bl6/J mice (age 8–10 weeks, n = 12) and cut into four rings (2 mm in length). These were either used immediately for short-term (4 h), or incubated in a 24 well plate for extended (24 h), exposure to 7-oxysterols. For short-term exposures, aortic rings were mounted on intra-luminal wires in a small vessel wire myograph [19,20] containing DMEM without L-Arg (37°C, continuously perfused with 95%O2: 5% CO2) [14]. After the vessels had been equilibrated at their optimum resting force they were contracted with KCl (125 mM, 3 times) to confirm viability and then incubated in the presence of: (1) 7-KC (25 μM in DMEM without L-Arg), (2) 7βOH (20 μM in DMEM without L-Arg) or (3) vehicle alone (ethanol, with 50 μg/ml BHT in DMEM without L-Arg), for 4 h (2 rings/treatment/mouse). The incubating medium was replaced every 60 min. After 4 h cumulative concentration–response curves were obtained for 5-hydroxytryptamine (5-HT; 1 × 10−9–1 × 10−4 M) and noradrenaline (NA; 1 × 10−9–1 × 10−4 M). In addition, cumulative concentration–response curves were obtained for the vasodilators, acetylcholine (ACh; 1 × 10−9–1 × 10−4 M, endothelium-dependent) and sodium nitroprusside (SNP; 1 × 10−5–1 × 10−4 M, endothelium-independent), following contraction with a sub-maximal concentration of 5-HT (3 × 10−2–1 × 10−5 M). Contractile responses are expressed as force per unit length (mN/mm).

Relaxations were expressed as a percentage of the contraction in response to the EC50 of 5-HT (% 5-HT).

For extended exposures [14], aortic rings were placed in a 24 well plate and immersed in 1 ml DMEM (without L-Arg) containing either 7-KC (25 μM), 7βOH (20 μM), or vehicle (ethanol with 50 μg/ml BHT) and incubated overnight in a humidified incubator (37°C; 5% CO2). These vessels were then mounted in a myograph and functional studies performed, as described above, in the continued presence of the appropriate 7-oxysterol or vehicle.
a stream of argon and residues dissolved in chloroform:methanol (2:1, 350 μl) before storing at −20 °C for analysis by GC/MS. Results were subsequently corrected for aortic ring weight. In all assays appropriate positive controls were included, with aortic rings incubated with [3H] 4-dehydrocorticosterone or [3H] 4-dehydrocorticosterone (30 nM) to verify the activity of 11β-HSD isoforms. Samples were processed for analysis as before [27].

2.5.2. In kidney

Murine kidneys contain both isoforms of 11β-HSD. Homogenates of kidneys from Hsd11b1−/− mice (which lack 11β-HSD1) were used as a source of murine 11β-HSD2, with kidneys from C57Bl/6j mice as controls. Kidneys were homogenized in phosphate buffer as detailed [10]. Homogenates (400 μg/ml) were incubated with 7-oxosterols (20 μM) and the appropriate cofactor (2 mM); NAD+ or NADP+ for dehydrogenase reactions; NADH or NADPH for reductase reactions. In all assays conversion of dexamethasone (Dex) and 11-dehydrodexamethasone (11-DHDex; 40 μM) was used as a positive control for confirmation of 11β-HSD isozyme activity [28].

2.6. Chromatographic analyses

2.6.1. Analysis of 7-oxosteroids by gas chromatography/mass spectrometry (GC/MS)

7-Oxosteroids and cholesterol were converted to trimethylsilyl ether derivatives using a pyridine:hexamethyldisilazan:trimethylchlorosilane mixture (350 μl; 3:2:1, v/v/v) [29,30]. The derivatized cholesterol metabolites were dissolved in 2% N,O-Bis(trimethylsilyl)trifluoroacetamide (BSTFA) in decane (80 μl) and eluted as follows: initial temperature 180 °C (1 min), increased by 35 °C/min until 270 °C was achieved (1 min) and then increased by 4 °C/min to 300 °C (12 min). The oven was then cooled by −10 °C/min to 250 °C (1 min). The injection temperature was 270 °C.

A capillary gas chromatograph (Trace GC, Thermo) was coupled to an ion-trap, Polaris Q (Thermo, Hemel Hempstead, UK) mass spectrometer (MS) and equipped with a BPX5 capillary column (25 m, 0.32 mm internal diameter and 0.25 μm film thickness; SGE, Alva, UK) and operated in SIM mode with electron impact (70 eV), ion source, transfer line and interface temperatures of 200 °C, 220 °C and 250 °C respectively. Derivatives of 7-oxosteroids and cholesterol were quantified by monitoring the following ions (m/z): 7-KC (472, 16.5 min), 7α/7βOH (456, 12.3 & 14.1 min), d7-7-KC (479, 16.35 min), d7-7αOH (463, 13.8 min) and d7-cholesterol (375, 12.9 min). Limits of detection were assigned as 3:1 signal to noise ratio. Compounds were quantified by the ratio of area under peak of interest to area under peak of internal standard against a standard curve.

2.6.2. Quantitation of steroids by high pressure liquid chromatography

Radio-labelled glucocorticoids were separated by reverse phase HPLC (Symmetry C8 column maintained at 35 °C; column length, 15 cm, internal diameter 4.6 mm, pore size 5 μm, Waters, Edinburgh, UK) and quantified by on-line liquid scintillation counting (2 ml/min; Goldflow, Meridian, Surrey, UK). Total run time was 35 min (elution times of epi-cortisol, 11-dehydrocorticosterone and corticosterone were typically 12 min, 21 min and 31 min, respectively, with mobile phase of water:acetonitrile:methanol (60:15:25) at 1 ml/min). Dex and 11-DHDex were separated using a mobile phase of water:acetonitrile:methanol (55:20:25) at 1 ml/min with typical retention times for epi-cortisol (10 min), 11-DHDex (12 min) and Dex (16 min). UV detection of all steroids was achieved at 240 nm and epi-cortisol was used as an internal standard. Steroids were quantified by the ratio of area under peak of interest to area under peak of internal standard against a standard curve.

2.7. Statistical analysis

All data are mean ± standard error of the mean (SEM) where n indicates the number of different animals. Values were compared using unpaired Student’s t-tests or 1-way ANOVA with Dunnett’s multiple comparison post-tests, as appropriate. All analyses were performed using Graph Pad Prism v5.0 (GraphPad Software Inc. San Diego, USA). Statistical significance was assumed when p < 0.05.

3. Results

3.1. 7-KC, but not 7βOH, alters vascular function in vitro

Short-term exposure (4 h) of aortae from C57Bl/6j mice to 7-KC (25 μM), but not 7βOH (20 μM), produced a small reduction (p = 0.049) in NA-induced maximum contraction (Emax), but had no effect on the sensitivity (pD2) of this response (Fig. 1A, B; Table 1A). Prolonged incubation with either 7-KC or 7βOH did not alter endothelium-dependent relaxation to ACh (Fig. 1C, D). An apparent increase in maximal response to endothelium-independent, SNP-mediated vasorelaxation after incubation with either 7-KC (p = 0.05) or 7βOH (p = 0.08) was of borderline statistical significance (Fig. 1E, F).

Long-term (24 h; Fig. 2) exposure of aortae from C57Bl/6j mice to 7-KC (25 μM), but not 7βOH (20 μM), produced a reduced maximum contraction (Emax, p = 0.049), but no change in sensitivity (pD2) to NA (Fig. 2A, B; Table 1B). Prolonged incubation with either 7-oxysterol had no effect on 5-HT-mediated contraction or endothelium-dependent (Fig. 2C, D) or -independent (Fig. 2E, F) relaxation (Table 1B).

3.2. 7-Oxosteroids are present in the mouse aortic wall and altered by deletion of 11β-HSD1

7-KC (3.52 ± 2.85 nmol/g tissue) and 7βOH (0.40 ± 0.15 nmol/g) were both detected in the mouse thoracic aortae with levels of 7-KC significantly higher than 7βOH (p = 0.05; n = 12). In aortae from Hsd11b1−/− mice, 7-KC was only present in levels above the limit of detection in 3 (of 8) samples and 7βOH was also low (0.12 ± 0.02 nmol/mg). Plasma levels of 7-oxosteroids were not different in Hsd11b1−/− mice compared with C57Bl/6j mice (7-KC: 0.133 ± 0.016 versus 0.091 ± 0.022 μM; 7βOH 0.024 ± 0.002 versus 0.023 ± 0.005 μM, respectively) although total plasma cholesterol was lower (0.45 ± 0.14 versus 1.03 ± 0.19 μM, p < 0.05).

3.3. 7-Oxosteroids are metabolized by 11β-HSD1 but not by 11β-HSD2

As expected [15], glucocorticoids were inter-converted by incubation with intact mouse aortic rings. The velocity of reduction of 7-KC (to 7-KC) was similar following incubation with mouse aortic rings. In contrast to glucocorticoids, however, the velocities of reduction of 7-KC (to 7-KC) were considerably (0.12 ± 0.02 nmol/mg) were both detected in the mouse thoracic aortae with levels of 7-KC significantly higher than 7βOH (p = 0.05; n = 12). In aortae from Hsd11b1−/− mice, 7-KC was only present in levels above the limit of detection in 3 (of 8) samples and 7βOH was also low (0.12 ± 0.02 nmol/mg). Plasma levels of 7-oxosteroids were not different in Hsd11b1−/− mice compared with C57Bl/6j mice (7-KC: 0.133 ± 0.016 versus 0.091 ± 0.022 μM; 7βOH 0.024 ± 0.002 versus 0.023 ± 0.005 μM, respectively) although total plasma cholesterol was lower (0.45 ± 0.14 versus 1.03 ± 0.19 μM, p < 0.05).
96 ± 6% of added substrates being recovered. 7-KC was not interconverted with 7βOHC in aortic rings (data not shown).

Hsd11b1−/− mouse kidney homogenates (a rich source of 11β-HSD2; [31]) were used to determine whether 7-oxysterols are metabolised by this isozyme. As with the aortic rings, conversion of glucocorticoids was used as a positive control for activity of 11β-HSD2 [14,27]. As anticipated, glucocorticoids were metabolized by mouse renal homogenates with preferential generation of 11-DHDex from Dex (oxidation; not shown). In contrast, renal homogenates did not inter-convert any of the 7-oxysterols (7αOHC, 7βOHC or 7-KC). Unrecovered substrate was ~3% or lower for each compound (7αOHC, 1.9 ± 0.7%; 7βOHC, 3.2 ± 0.3%; KC, 2.1 ± 0.3%).

4. Discussion

This study shows for the first time that 11β-HSD1, but not 11β-HSD2, catalyses the conversion of 7-oxysterols in the vascular wall. Previous work has shown that murine and human 11β-HSD1

Fig. 1. Short-term (4 h) exposure to 7-ketocholesterol induces agonist-specific functional changes in isolated mouse aorta. Endothelium-intact aortic rings from C57Bl6j mice were incubated (4 h) with 7-ketocholesterol (7-KC, 25 μM open squares) or 7β-hydroxycholesterol (7βOHC, 20 μM, open squares) and compared with vehicle (ethanol containing 50 μg/ml butylated hydroxytoluene)-treated control (filled squares). Incubation with 7-KC (A), but not 7βOHC (B), produced a small reduction of noradrenaline (NA)-mediated contraction (p = 0.04). Incubations had no effect on acetylcholine (ACh)-mediated relaxation (C, D) whereas 7-KC (E) (but not 7βOHC (F)), produced a trend towards increased sodium nitroprusside (SNP)-mediated relaxation (p = 0.054). Relaxations were expressed on a scale where the response to 5-HT represented 100% and return to baseline was expressed as 0%. All points represent mean ± SEM, compared by 1-way ANOVA with Tukey’s post hoc test, n = 6–8.
that was not observed with 7bOHC. The mechanism involved is unclear but the effect was selective for noradrenaline, suggesting an impairment in the α1-adrenoceptor signalling pathway. Impaired contractility is consistent with 7-KC at this concentration having detrimental effects on vascular smooth muscle cells [35]. These results suggest, therefore, that the balance of 7-KC and 7bOHC may have functional and structural implications in the arterial wall.

The concentrations of 7-oxysterols in the vessels of C57Bl6j mice are consistent with those reported previously in human plasma and vessels [1,24]. Since circulating 7-oxysterols can be sequestered by cells in the vessel wall [37], we assessed the potential of vascular 11b-HSD1 to inter-convert 7-oxysterols in this tissue. Plasma 7-oxysterol levels were not altered in Hsd11b1−/− mice although total plasma cholesterol was substantially lower. Consistent with previous reports of reduced intra-vascular cholesterol accumulation with inhibition of 11b-HSD1 [38], we found lower levels of all 7-oxysterols in the aortae of Hsd11b1−/− mice. It was, therefore, difficult to assess intra-vascular 7-KC/7bOHC ratios, since 7-KC levels in particular were near to the detection limit, but the data suggest that 7-KC levels are disproportionately reduced in Hsd11b1−/− mice, consistent with the enzyme acting predominantly as an oxidase (converting 7bOHC to 7-KC) in vivo.

The ex vivo incubation of aortic rings described here has not previously been used to assess inter-conversion of 7-oxysterols. This approach confirmed that the stability of 7-oxysterols can be preserved during incubation, as both 7-KC and 7bOHC were successfully recovered from DMEM. It had been postulated that 7-oxysterols may be taken up by the vessels during incubation but the percentage recovery of 7-oxysterols from reaction mixtures did not support this. Preparation of concentrated stock solutions of the 7-oxysterols proved unexpectedly difficult, despite using published methodology [3], with oxysterols precipitating at high concentrations. Based on our own experiences and advice from other groups 7-oxysterol solutions were prepared in DMEM containing FCS containing an antioxidant (BHT; to prevent oxidative degradation of the lipids [3]). It is unlikely that BHT would have a detrimental effect on vascular function as it did not alter histamine-induced NO production in cultured HUVECs [32].

Ex vivo assays clearly demonstrated that incubation of 7-oxysterols with mouse aortic rings results in the conversion of 7bOHC to 7-KC and 7-KC to 7bOHC, but not inter-conversion of 7aOHC and 7-KC. This is consistent with results generated in rats [9,10] and humans [39] but contrasts with the demonstration that 11b-HSD1 in hamsters can inter-convert 7aOHC and 7-KC [40]. The ability of 11b-HSD1 to inter-convert 7-oxysterols explains why carbeneoxolone, a non-selective 11b-HSD inhibitor, attenuates 7-oxysterol metabolism in rat hepatic microsomes [10]. Interestingly, in contrast to the predominant reductase direction (11-dehydrocorticosterone to corticosterone) shown for metabolism of glucocorticoids, murine vascular 11b-HSD1 showed similar activity as both reductase (7bOHC to 7-KC) and dehydrogenase (7-KC to 7bOHC) for inter-conversion of oxysterols, consistent with previous reports in liver [9,39]. Under these assay conditions, the reaction velocity for inter-conversion of oxysterols was considerably (approximately 10-fold) higher than for reduction of 11-dehydrocorticosterone. This contrasts with the demonstration of similar reaction velocities observed in other studies [9,40] and is likely to be a consequence of study design as substrate concentrations were higher (~800×) for the oxysterols than for the glucocorticoids.

Residual metabolism of glucocorticoids in aortae from Hsd11b1−/− mice is consistent with vascular 11b-HSD2 expression [14,20]. Virtually no residual inter-conversion of 7bOHC and 7-KC converts 7-KC to 7bOHC in the liver and in cultured adipocytes [8,9]. We provide evidence that murine 11b-HSD1 reduces 7-KC to 7bOHC in the vessel wall but, furthermore, that it also oxidizes 7bOHC to 7-KC. Use of Hsd11b1−/− mice confirmed that 11b-HSD1 was the sole enzyme responsible for metabolism of 7-KC and 7bOHC in the aortic wall and that deletion of 11b-HSD1 alters vascular 7-oxysterol concentrations. Functional investigations showed differential effects of 7-KC and 7bOHC on vascular function, suggesting that this 11b-HSD1-mediated inter-conversion of 7-oxysterols may influence 7-KC-mediated inhibition of arterial contraction.

7-KC and 7bOHC have both been shown previously to inhibit endothelium-dependent vasorelaxation [32], cause endothelial cell death, and induce production of radical oxygen species [17,33]. This is consistent with the ability of oxidized lipids to impair the endothelium-dependent relaxation of aortic segments from hyperlipidaemic mice [34]. The lack of impact of exposure to oxysterols on endothelium-dependent relaxation was surprising given the previous indications that both 7-KC and 7bOHC inhibit endothelial function [2,3,32] ex vivo. One possible explanation for lack of effect on vasorelaxation is the use of a low concentration of 7-oxysterol (20–25 μM) compared with previous studies (180–270 μM; [2,3,32]). The concentrations used for our investigations were the highest we could achieve without precipitation and are consistent with that used (25 μM) to show 7-oxysterol-mediated smooth muscle apoptosis in vitro [35]. Furthermore, a recent investigation using high concentrations of 7-KC (205 μM) found no effect of ex vivo incubation on ACh-mediated relaxation of mouse aorta [36].

Intriguingly at the concentrations used in this investigation, there was an inhibition of smooth muscle cell contraction by 7-KC
was observed in aortae from mice lacking 11β-HSD1. Lack of 7-oxysterol metabolism by 11β-HSD2 was confirmed using kidney homogenates (since the kidney is rich in 11β-HSD2 [15]; using kidneys from Hsd11b1<sup>−/−</sup> mice ensured that there was no interference from this isozyme). This finding is consistent with the previous attribution of 7-oxysterol metabolism solely to the action of 11β-HSD1 in hamster [40], rat [9,10], guinea pig [9,41] and human [39]. There was, however, a notable loss of substrate in the reaction mixtures; suggesting incomplete recovery of substrate, non-enzymatic degradation, or formation of alternative products [42]. There was no loss of substrate in blank samples (containing buffer but no tissue homogenate), confirming chemical stability of 7-oxysterols during the incubation.

Direct action on the cells of the arterial wall may not present the only mechanisms through which oxysterols can influence regulation of arterial function and structure. Previous work in our group [43] has indicated that the ability of oxysterols to act as substrates for 11β-HSD1 also makes them potential competitive inhibitors of glucocorticoid metabolism. This presents the possibility that endogenous 7-oxysterols contribute to regulation of 11β-HSD1-dependent glucocorticoid generation. Glucocorticoids can interact directly with the arterial wall to enhance vasoconstriction [44], impair endothelium-dependent relaxation [45], inhibit angiogenesis [27] and reduce vascular lesion formation. There is increasing evidence that these interactions are regulated by the activity of 11β-HSD1 [27,38]. However, it is notable that no systematic
difference in vascular function has been observed in vessels from Hsd11b1−/− mice [20], so whether alterations in 7-oxysterol or glucocorticoids influences physiological vascular function remains uncertain. Perhaps interactions of oxysterols with 11β-HSD1 are more important in pathology. In healthy individuals, the maximum concentrations of 7-oxysterols [46,47] are lower than those in patients with atherosclerosis who may have levels of 7-oxysterols in the micromolar range [1]. It is plausible that inhibition of 11β-HSD1-mediated glucocorticoid generation in conditions of 7-oxysterol excess may have an indirect impact on arterial function and remodelling.

Metabolism of 7-oxysterols by 11β-HSD1 may also have implications for the development of new therapies. Selective 11β-HSD1 inhibition prevents atherosclerosis [38] and is being developed for treatment of cardiovascular risk factors [48], but the mechanisms responsible for this atheroprotective effect have not been demonstrated. It is conceivable that the beneficial effects of 11β-HSD1 inhibition are a consequence of prevention of 7-oxysterol interconversion as well as glucocorticoid metabolism.

5. Conclusions

11β-HSD1 influences 7-oxysterol concentrations within the arterial wall. By altering the balance of 7-ketocholesterol and 7β-hydroxycholesterol, 11β-HSD1 may modulate its specific effects on vascular function, especially in disease states in which oxysterol levels are increased.

Acknowledgements

TM received a PhD studentship from the Wellcome Trust and the work was supported by funding from the British Heart Foundation. The authors would like to acknowledge support from the BHF Centre of Research Excellence Award.

References

[1] A.J. Brown, W. Jessup, Oxysterols: sources, cellular storage and metabolism, and new insights into their roles in cholesterol homeostasis, Molecular Aspects of Medicine 30 (2009) 111–122.

[2] V. Deckert, L. Persegol, L. Viens, G. Lizard, A. Athias, C. Lallemant, P. Gambert, L. Lagrost, Inhibitors of arterial relaxation among components of human oxidized low-density lipoprotein: cholesterol derivatives oxidized in position 7 are potent inhibitors of endothelium-dependent relaxation, Circulation 95 (1997) 723–731.

[3] V. Deckert, A. Brunet, F. Lantoine, G. Lizard, E.M.-v. Brussel, S. Monier, L. Lagrost, M. van-Duifhuis, P. Gambert, M.A. Devynck, Inhibition by cholesterol oxides of NO release from human vascular endothelial cells, Arteriosclerosis, Thrombosis, and Vascular Biology 18 (1998) 1054–1060.

[4] G. Lizard, S. Gueldry, V. Deckert, P. Gambert, L. Lagrost, Evaluation of the cytotoxic effects of some oxysterols and of cholesterol on endothelial cell formation and caspase-dependent polar lipid accumulation, Histochemistry and Cell Biology 127 (2007) 609–624.

[5] J.R. Seckl, B.R. Walker, Minireview: 11β-hydroxysteroid dehydrogenase type 1: a tissue-specific amplifier of glucocorticoid action, Endocrinology 142 (2001) 1371–1376.

[6] Y. Kotelevtsev, R.W. Brown, S. Fleming, C. Kenyon, C.R.W. Edwards, J.R. Seckl, J.J. Mullins, Hypertension in mice lacking 11β-hydroxysteroid dehydrogenase type 2, Journal of Clinical Investigation 103 (1999) 683–689.

[7] M. Wamilt, R. Andrew, K.E. Chapman, J. Street, N.M. Morton, J.R. Seckl, 7-Oxysterols modulate glucocorticoid activity in adipocytes through competition for 11β-hydroxysteroid dehydrogenase type 1, Endocrinology 149 (2008) 5909–5918.

[8] M. Huit, B. Elleby, N. Shafqat, S. Svensson, A. Rane, H. Evren, L. Abrahamsen, U. Oppermann, Human and rodent type 1 11β-hydroxysteroid dehydrogenases are 7β-hydroxysterolesterol dehydrogenases involved in oxysterol metabolism, Cellular and Molecular Life Sciences 61 (2004) 992–999.

[9] R.A.S. Schweizer, Z. Marcel, Z. Balazs, D. Bernhard, A. Odermatt, Rapid hepatic metabolism of 7-ketocholesterol by 11β-hydroxysteroid dehydrogenase type 1: species-specific differences between the rat, human, and hamster enzyme, Journal of Biological Chemistry 279 (2004) 18415–18424.

[10] B.R. Walker, J.L. Yau, L.P. Brett, J.R. Seckl, C. Monder, B.C. Williams, C.R. Edwards, 11β-Hydroxysteroid dehydrogenase in vascular smooth muscle and heart: implications for cardiovascular responses to glucocorticoids, Endocrinology 129 (1991) 3305–3312.

[11] N.M. Morton, J.M. Paterson, H. Masuzaki, M.C. Holmes, B. Staels, C. Fievet, B.R. Walker, J.S. Flier, J.J. Mullins, J.R. Seckl, Novel adipose tissue-mediated resistance to diet-induced visceral obesity in 11β-hydroxysteroid dehydrogenase type 1-deficient mice, Diabetes 53 (2004) 931–938.

[12] Z. Krzoeski, Z. Chai, The role of 11β-hydroxysteroid dehydrogenases in the cardiovascular system, Endocrine Journal 50 (2003) 485–489.

[13] C. Christy, P.W.F. Hadoke, J.M. Paterson, J.J. Mullins, J.R. Seckl, B.R. Walker, 11β-Hydroxysteroid dehydrogenase type 2 in mouse aorta: localization and influence on response to glucocorticoids, Hypertension 42 (2003) 580–587.

[14] A.R. Dover, P.W.F. Hadoke, L.J. Macdonald, E. Miller, D.E. Newby, B.R. Walker, Intravascular glucocorticoid metabolism during inflammation and injury in mice, Endocrinology 148 (2007) 166–172.

[15] Y. Kotelevtsev, M.C. Holmes, A. Burchell, P.M. Houston, D. Schmoll, P. Jamieson, R. Best, R. Brown, C.R. Edwards, J.R. Seckl, J.J. Mullins, 11β-Hydroxysteroid dehydrogenase type 1 knockout mice show attenuated glucocorticoid-
inducible responses and resist hyperglycemia on obesity or stress, Proceedings of the National Academy of Sciences 94 (1997) 14924–14929.

[17] G. Lizard, S. Monier, C. Cordelet, L. Gesquiere, V. Deckert, S. Gueldry, L. Lagrost, P. Gambert, Characterization and comparison of the mode of cell death, apoptosis versus necrosis, induced by 7β-hydroxysteroid and 7-ketosteroid in the cells of the vascular wall, Arteriosclerosis, Thrombosis, and Vascular Biology 19 (1999) 1190–1200.

[18] C.J. Seye, M.W.M. Knaapen, D. Daret, C. Desgranges, A.G. Herman, M.M. Kockx, H. Bult, 7-Ketosteroid induces reversible cytochrome c release in smooth muscle cells in absence of mitochondrial swelling, Cardiovascular Research 64 (2004) 144–153.

[19] R. Hynynen, M. Suchanek, J. Spandl, N. Back, C. Thiele, V.M. Olkkonen, OSBP-related protein 2 (ORP2) is a sterol receptor on lipid droplets that regulates the metabolism of neutral lipids, Journal of Lipid Research 50 (2009) 1305–1315.

[20] P.W.F. Hadoke, C. Christy, Y.V. Kotelevtsev, M. Umetani, P.W. Shaul, D.J. Mangelsdorf, D.P. McDonnell, 27-hydroxycholesterol and 7-ketocholesterol, as tools to investigate the isozymes of 11β-hydroxysteroid dehydrogenase, Circulation 104 (2001) 2832–2837.

[21] K. Endo, T. Oyama, A. Saiki, N. Ban, M. Ohira, N. Koide, T. Murano, W. Hatanabe, M. Nishii, M. Miura, K. Sekine, Y. Miyashita, K. Shirai, Determination of serum 7-ketosteroid concentrations and their relationships with coronary multiple risks in diabetes mellitus, Diabetes Research and Clinical Practice 80 (2008) 63–68.

[22] H.N. Hodis, S. Hashimoto, W.J. Mack, A. Sevanian, Probucol reduces oxysterol formation in hypertensive rabbits, Hypertension 36 (2000) 435–441.

[23] W. Siems, S. Quast, D. Peter, W. Augustin, F. Carluccio, T. Grune, A. Sevanian, H. Hampi, I. Wiswedel, Oxysterols are increased in plasma of end-stage renal disease patients, Kidney and Blood Pressure Research 28 (2005) 302–306.

[24] A.J. Brown, S. Leong, R.T. Dean, W. Jessup, 7-Hydroxycholesterol and its products in oxidized low density lipoprotein and human atherosclerotic plaque, Journal of Lipid Research 38 (1997) 1730–1745.

[25] H.N. Hodis, D.W. Crawford, A. Sevanian, Cholesterol feeding increases plasma and aortic tissue cholesterol oxide levels in parallel: further evidence for the role of cholesterol oxidation in atherosclerosis, Atherosclerosis 89 (1991) 117–126.

[26] N. Freeman, A. Ruisinol, M. Linton, D. Hachey, S. Fazio, M. Sinensky, D. Thewke, Acyl-coenzyme A cholesterol acyltransferase promotes oxidized LDL/oxysterol-induced apoptosis in macrophages, Journal of Lipid Research 46 (2005) 1933–1943.

[27] G.R. Small, P.W.F. Hadoke, S. Loug, A.R. Dover, D. Armour, C. Monder, J.W. Funder, Characterization of hamster liver microsomal 7α-hydroxycholesterol dehydrogenase, similarity to type I 11β-hydroxysteroid dehydrogenase (11β-HSD1), Journal of Biological Chemistry 273 (1998) 16223–16228.

[28] Y. Maeda, H. Nagatomo, F. Uchiyama, J. Nagatomo, M. Yamada, H. Shiotsuki, S. Sato, M.H. Kai, K.H. Kondo, A comparative study of the conversion of 7-hydroxycholesterol in rabbit, guinea pig, rat, hamster, and chicken, Steroids 67 (2002) 703–708.

[29] C.D. DuSell, M. Unetani, P.W. Shaul, D.J. Mangelsdorf, D.P. McDonnell, 27-Hydroxycholesterol is an endogenous selective estrogen receptor modulator, Molecular Endocrinology 22 (2008) 65–77.

[30] T. Mitic, S. Shave, S.P. Webster, I. McNae, D.F. Cobice, N. Semjonous, R.E. Dakin, K.E. Chapman, G.G. Laverty, P.W.F. Hadoke, B.R. Walker, R. Andrew, The role of 7-oxosterols to inhibit dehydrogenation of glucocorticoids by 11β-hydroxysteroid dehydrogenase type 1, submitted for publication.

[31] M.E. Ullian, Cardiovascular Research 41 (1999) 55–64.

[32] G.J. Johns, A.M. Dorrance, N.L. Tramontini, R.C. Webb, Glucocorticoids inhibit tetradroibiotin-dependent endothelial function, Experimental Biology and Medicine 226 (2001) 27–31.

[33] M. Nishio, E. Usui, T. Kawamoto, H. Kubo, K. Fujimoto, M. Furukawa, S. Honma, M. Makishima, K.-i. Honma, Y. Kato, Multiple mechanisms regulate circadian expression of the gene for cholesterol 7α-hydroxylase (cyp7a), a key enzyme in hepatic bile acid biosynthesis, Journal of Biological Rhythms 22 (2007) 299–311.

[34] D.F. Reilly, E.J. Westgate, G.A. Fitzgerald, Peripheral circadian clocks in the vasculature, Arteriosclerosis, Thrombosis, and Vascular Biology 27 (2007) 1674–16705.

[35] J. Rosenstock, S.E. Inzucchi, J. Seufert, P.R. Fleck, C.A. Wilson, Q. Meekis, Initial combination therapy with alogliptin and pioglitazone in drug-naive patients with type 2 diabetes, Diabetes Care 33 (2010) 2406–2408.