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11β-hydroxysteroid dehydrogenase type 1 deficiency in bone marrow-derived cells reduces atherosclerosis

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*British Heart Foundation Centre for Cardiovascular Science and †Medical Research Council (MRC) Centre for Inflammation Research, The Queen’s Medical Research Institute, and ‡MRC Centre for Regenerative Medicine, University of Edinburgh, Edinburgh, UK; and §Université de Lille Nord de France, Institut National de la Santé et de la Recherche Médicale (INSERM), Unité Mixte de Recherche (UMR) 1011, Université Droit et Sante de Lille (UDSL), Institut Pasteur de Lille, Lille, France

ABSTRACT 11β-Hydroxysteroid dehydrogenase type-1 (11β-HSD1) converts inert cortisol into active cortisol, amplifying intracellular glucocorticoid action. 11β-HSD1 deficiency improves cardiovascular risk factors in obesity but exacerbates acute inflammation. To determine the effects of 11β-HSD1 deficiency on atherosclerosis and its inflammation, atherosclerosis-prone apolipoprotein E-knockout (ApoE-KO) mice were treated with a selective 11β-HSD1 inhibitor or crossed with 11β-HSD1-KO mice to generate double knockouts (DKOs) and challenged with an atherogenic Western diet. 11β-HSD1 inhibition or deficiency attenuated atherosclerosis (74–76%) without deleterious effects on plaque structure. This occurred without affecting plasma lipids or glucose, suggesting independence from classical metabolic risk factors. KO plaques were not more inflamed and indeed had 36% less T-cell infiltration, associated with 36% reduced circulating monocyte chemoattractant protein-1 (MCP-1) and 36% lower lesional vascular cell adhesion molecule-1 (VCAM-1). Bone marrow (BM) cells are key to the atheroprotection, since transplantation of DKO BM to irradiated ApoE-KO mice reduced atherosclerosis by 51%. 11β-HSD1-null macrophages show 76% enhanced cholesterol ester export. Thus, 11β-HSD1 deficiency reduces atherosclerosis without exaggerated lesional inflammation independent of metabolic risk factors. Selective 11β-HSD1 inhibitors promise novel antiatherosclerosis effects over and above their benefits for metabolic risk factors via effects on BM cells, plausibly macrophages.—Kipari, T., Hadoke, P. W. F., Iqbal, J., Man, T. Y., Miller, E., Coutinho, A. E., Zhang, Z., Sullivan, K. M., Mitic, T., Livingstone, D. E. W., Schrecker, C., Samuel, K., White, C. I., Boughlel, M. A., Chinetti-Gbaguidi, G., Staels, B., Andrew, R., Walker, B. R., Savill, J. S., Chapman, K. E., Seckl, J. R. 11β-hydroxysteroid dehydrogenase type 1 deficiency in bone marrow-derived cells reduces atherosclerosis. FASEB J. 27, 000–000 (2013). www.fasebj.org

Key Words: atherogenesis · glucocorticoids · inflammation

Chronic inflammation is a key process in atherogenesis, with extensive macrophage and lymphocyte invasion of lesions, promoting pathogenesis (1–6). Glucocorticoids in high doses suppress inflammation, but glucocorticoid pharmacotherapy (7, 8) or Cushing’s disease (9, 10) exacerbate atherosclerosis and increase
cardiovascular events, presumably via glucocorticoid exacerbation of systemic cardiovascular risk factors.

11β-Hydroxysteroid dehydrogenase type 1 (11β-HSD1) catalyzes regeneration of active glucocorticoids (cortisol, corticosterone) from inert 11-keto forms (corticosterone, 11-dehydrocorticosterone), acting as an intracellular amplifier of glucocorticoid action. 11β-HSD1 is up-regulated in adipose tissue in obesity in humans (11) and rodents (12), leading to the notion of intra-cellular Cushing’s syndrome of adipose tissue as a cause of obesity and its cardiometabolic consequences. Indeed, transgenic overexpression of 11β-HSD1 in adipose tissue produces local, but not systemic, glucocorticoid excess and causes visceral obesity and metabolic syndrome (13). Conversely, 11β-HSD1 deficiency protects mice from the adverse metabolic consequences of dietary obesity (14–16). A selective 11β-HSD1 inhibitor lowered blood glucose, glycated hemoglobin A1c (HbA1c) and cholesterol in patients with type 2 diabetes (17). These metabolic effects are presumed atheroprotective. Indeed in mice, a selective 11β-HSD1 inhibitor that reduced circulating cholesterol also reduced intra-aortic cholesterol, but this study did not address lesion structure or, crucially, inflammation (18). Another inhibitor had no effect on atherosclerotic lesion size (19). The key concern is whether or not lesions are more inflamed or structurally vulnerable.

11β-HSD1 is expressed in differentiated/activated macrophages and lymphocytes and is up-regulated during an inflammatory response (20–22) in which glucocorticoids promote macrophage phagocytosis of apoptotic neutrophils (23). 11β-HSD1 deficiency delays acquisition of phagocytic competence by macrophages and exacerbates acute inflammation, at least in some models (21, 24, 25). Glucocorticoids, albeit in high doses, reduce the response to vascular injury and its associated inflammation (26), and they attenuate migration (27) and proliferation (28) of vascular smooth muscle cells, effects contributing to plaque stability. 11β-HSD1 in the vessel wall, though without effect on the contractility of normal vessels (29), amplifies anti-proliferative effects of glucocorticoids (30). Conversely, glucocorticoids reduce cholesteryl ester hydrolysis and export by macrophages (31) and inhibit formation of fibrous tissue (32, 33), processes contributing to plaque instability. Thus, the overall effects of 11β-HSD1 deficiency/inhibition on atherosclerotic plaques are uncertain, with systemic metabolic improvements potentially offset by worse lesional inflammation and changes in lesion structure. Indeed, any role for 11β-HSD1 in inflammatory/immune cells in atherogenesis is unknown. To address these key questions, we examined the effects of selective pharmacological inhibition or genetic deletion of 11β-HSD1 in apolipoprotein E-knockout (ApoE-KO) mice, a model of spontaneous atherogenesis on high cholesterol Western diet (WD).

**MATERIALS AND METHODS**

**Animals**

All animal experiments were carried out under the auspices of the UK Animals (Scientific Procedures) Act of 1986, and with approval from the University of Edinburgh Ethical Review Committee. Male, 11β-HSD1+/mice congenic on the C57BL/6j genetic background have been described previously (16). 11β-HSD1−/− mice were crossed with ApoE−/− mice (also congenic on C57BL/6j; Charles River, Margate, Kent, UK) to produce 11β-HSD1+/−, ApoE−/− double-knockout (DKO) mice, 11β-HSD1+/−, ApoE−/− heterozygote (het) mice, and apoE−/− (ApoE-KO) controls. Animals were born in the expected mendelian ratios, and DKO and het mice were indistinguishable from ApoE-KO mice at birth, weaning, and in adulthood. Genotyping using tail-tip DNA was performed as described previously (15). apoE−/− genotyping was achieved using hot start PCR with forward (exon 3, POS 285; 5′-AACCTTACTCTACAGAGGATGC-3′) and reverse (exon 4 pos 869; 5′-CGCTCATGTTCTCCTCATCATG-3′) primers. This amplified PCR products of 584 bp for the wild-type allele and 1500 bp for the null allele. All in vivo experiments and ex vivo analyses were performed blind to genotype.

**Induction, detection, and quantification of atherosclerosis**

The effects of short-term inhibition of 11β-HSD1 on atherosclerosis and lesion structure were assessed. Adult (10 wk old) male ApoE-KO mice were fed a high-cholesterol WD (D12079B; Research Diets, New Brunswick, NJ, USA) ad libitum, for 14 wk. For the last 8 wk of this period, mice were

<table>
<thead>
<tr>
<th>Table 1. Primer sequences for RT-PCR primers</th>
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<tr>
<td>Accession number</td>
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<td>NM_007393.3</td>
</tr>
<tr>
<td>NM_010927.3</td>
</tr>
<tr>
<td>NM_020590.3</td>
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</tbody>
</table>
randomized (balanced design, \(n=6\)/group) to receive either vehicle or a selective 11\(\beta\)-HSD1 inhibitor (compound 544 [3-(1-adamantyl)-6,7,8,9-tetrahydro-5\(\beta\)-(1,2,4)-triazolo[4,3-\(\alpha\)]azepine; ref. 18]; Enamine, Kiev, Ukraine). Mice consumed \(\sim 10\) mg/kg/d. This dose inhibited hepatic 11\(\beta\)-reductase activity by 52 \(\pm\) 4\% (\(n=3\)) 4 h after administration by oral gavage, consistent with previous reports (18).

To confirm specificity of action, male (4-wk or 4.5-mo-old) DKO, het, and ApoE-KO mice were similarly fed WD or normal chow diet for 14 wk. Body weight and food intake were measured weekly.

Animals were killed by asphyxiation (CO\(_2\)). blood was collected, and plasma was stored at \(-80\)\(^\circ\)C. The vascular tree was removed and cleaned of adherent tissue, and the aortic arch was used immediately for en face Sudan IV staining to identify neutral lipid incorporation (34), expressed as a percentage of the total surface area. The innominate artery was formalin fixed, paraffin embedded, cut into serial 4-\(\mu\)m sections, and stained with U.S. trichrome (UST; ref. 35).

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**Figure 1.** Selective 11\(\beta\)-HSD1 inhibition reduces atherosclerotic lesions in WD-fed ApoE-KO mice. A) i) On gross inspection, lesions were evident on the lesser curvature of the aortic arch (black arrow), in the innominate artery (red arrow) and at the origins of the left carotid and left subclavian arteries (black arrowheads). Lesions appeared to be smaller following 11\(\beta\)-HSD1 inhibition. ii) UST demonstrated large complex lesions in the innominate artery. iii) Immunohistochemistry with \(\alpha\)-SMA identified smooth muscle cells. iv) PSR staining identified collagen. B) Image analyses of these sections confirmed that short-term selective 11\(\beta\)-HSD1 inhibition reduced innominate artery atherosclerosis in ApoE-KO mice. C) 11\(\beta\)-HSD1 inhibition did not alter the proportion of smooth muscle cells in atherosclerotic lesions in the innominate artery of ApoE-KO mice. However, collagen content was increased following 11\(\beta\)-HSD1 inhibition, and smaller areas devoid of cells or collagen, probably reflecting extracellular lipid pools, were reduced, compared with ApoE-KO controls (\(n=6\)/group). Original view \(\times 40\). *\(P<0.05\) vs. vehicle control.
maximal cross-sectional narrowing were stained with picrosirius red (PSR) to show collagen content; quantification of picrosirius red staining was achieved using color deconvolution (Photoshop CS3 Extended, Adobe Systems, San Francisco, CA, USA) and expressed as a fraction of the total neointimal area, as described previously (38). All image analysis was performed blind to genotype or treatment.

Peritoneal inflammation

Peritonitis was induced in 12-wk-old female ApoE-KO or DKO mice after injection of 0.3 ml of 10% sterile thioglycollate (Sigma-Aldrich, Poole, UK). Peritoneal lavage cells were analyzed by flow cytometry after peritoneal lavage with 5 ml of PBS, 72 h postinjection.

Bone marrow (BM) transplantation

Ten-week-old male recipient ApoE-KO mice were housed under specific pathogen-free conditions in individually ventilated cages and given Baytril antibiotic (2.5%) in the drinking water for 1 wk before and 4 wk after BM transplantation. The mice were allowed to recover for 6 wk, and BM chimerism was verified by flow cytometric staining for 11β-HSD1 and CD45 antigen on blood leukocytes. 11β-HSD1 deficiency reduces atherosclerotic lesions in WD-fed ApoE-KO mice. (n=5) indicated that 94.3±1.3% of circulating leukocytes were donor derived. The mice were then placed on WD and were culled after 12 wk. The aortic arch and the abdominal aorta were formalin fixed, and optical projection tomography (OPT) analysis was used to quantify lesion and lumen volumes of the innominate artery and of the abdominal aorta. OPT scanning and quantification were performed as described previously (38). The cross-sectional area of innominate atherosclerotic lesions was also assessed, as above.

Immunohistochemistry

Immunohistochemistry was performed in serial sections taken at the point of maximal cross-sectional narrowing in each artery. Paraffin-embedded sections (4 µm) of innominate arteries were deparaffinized, blocked with normal rabbit or goat serum, incubated overnight (4°C) with primary antibodies against Mac-2 (Cedarlane, Tyne & Wear, UK; 1:6000), CD3e (Santa Cruz Biotechnology, Santa Cruz, CA, USA; 1:750), or α-smooth muscle actin (α-SMA; Sigma-Aldrich; 1:400) to detect macrophages, T cells, and smooth muscle cells, respectively. Antigen retrieval was performed using Borg Decloaker (Biocare Medical, Concord, CA, USA) as recommended by the manufacturer for CD3. Sections were visualized with DAB substrate (Vector Laboratories, Peterborough, UK) and counterstained with hematoxylin. Controls included a nonspecific IgG raised in the same species as the primary antibody. Immunoreactivity for α-SMA was quantified using color deconvolution (as described for collagen) and expressed as a fraction of the total neointimal area, as described previously (38). Mac-2 and CD3 staining were quantified by manually counting nuclei in areas of immunoreactivity and expressing the data as number of cells per square millimeter of lesion. All image analysis was performed blind to genotype.

Aortic function

Aortic ring functional responses to a vasoconstrictor (serotonin) and endothelium-dependent (acetylcholine) and -independent [sodium nitroprusside (SNP)] vasorelaxants were measured by isometric myography (29).

Plasma and serum measurements

Total plasma cholesterol and triglyceride levels were measured with assay kits (Infinity, Fisher Scientific, Loughborough, UK) and nonesterified fatty acid (NEFA) levels used

Figure 2. 11β-HSD1 deficiency reduces atherosclerotic lesions in WD-fed ApoE-KO mice. A) Atherosclerotic lesions were smaller in the innominate arteries of 4.5-mo-old DKO mice (n=10) fed high-cholesterol WD for 14 wk. Age-matched 11β-HSD1+/−, ApoE-KO het mice (n=3) also showed significant atheroprotection compared with age-matched ApoE-KO control mice (n=11). *P < 0.05. B) Lipid incorporation was also measured by en face Sudan IV staining of sections of the aortic arch. C) Quantification of Sudan IV staining showed that DKO mice had less lipid incorporation than ApoE-KO controls. (n=10–11/group). *P < 0.05, **P < 0.01 vs. ApoE-KO.
the Wako star C kit (Alpha Laboratories, Eastleigh, UK), according to the manufacturer’s instructions. Insulin levels were measured by ultrasensitive mouse insulin ELISA kit (Crystal Chem, Downers Grove, IL, USA) and glucose levels by the glucose hexokinase reagent (Infinity; Thermo Electron, Waltham, MA, USA). Monocyte chemoattractant protein 1 (MCP-1) ELISA on serum samples was performed as described previously (40). Fasting plasma triglycerides were measured using an in-house radioimmunoassay, as described previously (40).

**Flow cytometry**

BM cells were obtained after flushing the femurs with 5 ml of PBS. Tail-vein blood was collected into 3.9% sodium citrate. Spleens were pressed through a 40-µm cell strainer (BD Biosciences, Oxford, UK) to produce a single-cell suspension. Red blood cells (RBCs) in the BM and blood were lysed with BD lysis buffer (BD Biosciences, Oxford, Berkshire, UK), and RBCs from spleens were lysed with Sigma lysis buffer (Sigma-Aldrich). Cell suspensions were enumerated using a NucleoCassette and a NucleoCounter NC-100 (Chemometec, Allerød, Denmark). Nonspecific binding was blocked by incubating the cells with 10% mouse serum (MS; Sigma-Aldrich) for 10 min (4°C). Cells were stained in PBS with 10% MS conjugated antibodies at concentrations suggested by the supplier, for 30 min at 4°C. After washing, flow cytometric analyses were performed using BD FACS Calibur or LSRFortessa Cell Analyzer (BD Biosciences). Data analysis was performed using FlowJo 8.2 software (TreeStar, Ashland, OR, USA). Fluorescent flow-check fluorospheres (Beckman and Coulter, High Wycombe, UK) were added to blood, BM, and peritoneal lavage samples prior to analysis in order to calculate the absolute number of cells. Antibodies used were as follows. Anti-CD11b-peridinin chlorophyll protein cyanin 5.5 (PerCP/Cy5.5) or -fluorescein isothiocyanate (FITC) (clone M1/70), anti-F4/80-PerCP/Cy5.5 (clone BM8), anti-CD45-pacific blue (clone 30-F11), and anti-Ly6G-phycoerythrin-cyanine 7 (PECy7).

**Table 2. Effect of 11β-HSD1 deficiency on physiologic characteristics and metabolic parameters in ApoE-KO mice fed chow or WD for 14 wk**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Chow</th>
<th>ApoE KO</th>
<th>WD</th>
<th>DKO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body weight (g)</td>
<td>33.2 ± 1.2 (n=9)</td>
<td>33.40 ± 0.8 (n=7)</td>
<td>35.4 ± 0.5 (n=7)</td>
<td>37.0 ± 1.2 (n=8)†</td>
</tr>
<tr>
<td>Food intake (g/wk)</td>
<td>ND</td>
<td>ND</td>
<td>22.9 ± 2.0 (n=11)</td>
<td>21.1 ± 0.8 (n=11)</td>
</tr>
<tr>
<td>Cholesterol (mM)</td>
<td>7.6 ± 0.7 (n=14)</td>
<td>12.8 ± 1.2 (n=14)†</td>
<td>23.1 ± 1.9 (n=14)†††</td>
<td>22.3 ± 1.9 (n=14)†††</td>
</tr>
<tr>
<td>Triglycerides (mM)</td>
<td>0.92 ± 0.10 (n=14)</td>
<td>0.96 ± 0.11 (n=14)†</td>
<td>2.07 ± 0.21 (n=11)†††</td>
<td>1.40 ± 0.14 (n = 13)***†</td>
</tr>
<tr>
<td>Mesenteric adipose tissue weight (mg)</td>
<td>200.2 ± 35.8 (n=9)</td>
<td>300.7 ± 50.4 (n=7)</td>
<td>440.0 ± 64.6 (n=7)†</td>
<td>446.4 ± 87.4 (n=8)</td>
</tr>
<tr>
<td>Liver weight ratio (mg/g BW)</td>
<td>56.5 ± 3.4 (n=9)</td>
<td>53.2 ± 2.4 (n=7)</td>
<td>50.9 ± 2.9 (n=7)</td>
<td>47.0 ± 3.2 (n=8)</td>
</tr>
<tr>
<td>Spleen weight ratio (mg/g BW)</td>
<td>4.19 ± 0.34 (n=9)</td>
<td>3.04 ± 0.16 (n=7)</td>
<td>4.03 ± 0.51 (n=7)</td>
<td>5.60 ± 0.79 (n=8) ††</td>
</tr>
<tr>
<td>Thymus weight ratio (mg/g BW)</td>
<td>1.42 ± 0.16 (n=9)</td>
<td>1.30 ± 0.12 (n=7)</td>
<td>1.32 ± 0.10 (n=7)</td>
<td>1.18 ± 0.12 (n=8)</td>
</tr>
</tbody>
</table>

Data are means ± se. BW, body weight; ND, not determined. *P < 0.05, **P < 0.01 for effect of genotype; †P < 0.05, ††P < 0.01, †††P < 0.001 for effect of diet.

**Table 3. Effect of selective 11β-HSD1 inhibition in ApoE-KO mice on metabolic parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Vehicle</th>
<th>11β-HSD1 inhibitor</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative weight gain (g)</td>
<td>1.9 ± 0.2</td>
<td>0.8 ± 0.4*</td>
<td>0.03</td>
</tr>
<tr>
<td>Food intake (g/d)</td>
<td>8.0 ± 0.4</td>
<td>7.6 ± 0.2</td>
<td>0.3</td>
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<tr>
<td>Fasting plasma cholesterol (mM)</td>
<td>13.2 ± 1.5</td>
<td>12.0 ± 1.6</td>
<td>0.2</td>
</tr>
<tr>
<td>Fasting plasma triglycerides (mM)</td>
<td>2.04 ± 0.04</td>
<td>2.15 ± 0.06</td>
<td>0.2</td>
</tr>
<tr>
<td>Fasting plasma NEFA (mM)</td>
<td>2.7 ± 0.3</td>
<td>3.0 ± 0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>Fasting plasma glucose (AUC)</td>
<td>54630 ± 1504</td>
<td>50100 ± 4448</td>
<td>0.4</td>
</tr>
<tr>
<td>Fasting plasma insulin (AUC)</td>
<td>108 ± 15</td>
<td>71.6 ± 14.7</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Data are means ± se; n = 6/group. AUC, area under the curve. *P < 0.05 vs. vehicle control.
or -FITC (clone 1A8) were all from Biolegend (San Diego, CA, USA). Anti-CD115 phycoerythrin (PE; clone AFS98), anti-CD3-allophycocyanin (APC) or -PE (clone 17A2), and anti-CD45-PerCPCy5.5 (clone 30-F11) were all from BD Biosciences. Anti-CD4-FITC or -PerCPCy5.5 (clone RM4-5), anti-CD3-(clone PC61.5), and anti-CD8a-APC (clone N418), and anti-CD8a-APC (clone 7/4; AbD Serotec, Oxford, UK) were all from Biolegend (San Diego, CA, USA). Anti-CD115 phycoerythrin (PE; clone AFS98), or -FITC (clone 1A8) were all from Biolegend (San Diego, CA, USA). Anti-CD115 phycoerythrin (PE; clone AFS98), anti-CD3-allophycocyanin (APC) or -PE (clone 17A2), and anti-CD45-PerCPCy5.5 (clone 30-F11) were all from BD Biosciences. Anti-CD4-FITC or -PerCPCy5.5 (clone RM4-5), anti-B220-PE or -FITC (clone RA3-B2B), anti-CD25-APC (clone PC61.5), and anti-CD8a-APC (clone 53-6.7) were all from eBiosciences (Hatfield, UK). Anti-7/4/Alexa Fluor 647 (clone 7/4; AbD Serotec, Oxford, UK), anti-CD11c-APC (clone N418), and anti-B220-Pacific Orange (clone RA3-B2B) were all from Invitrogen. Negative controls were performed using isotype control antibodies. The gating scheme was used in flow cytometric analysis of mouse blood and BM was performed as described previously (42).

**Measurement of cholesterol uptake/efflux in macrophages**

Cholesterol efflux was measured (41) in BM-derived macrophages from 11β-HSD1-KO and C57BL/6J control mice, generated as described previously (21). Briefly, BM was flushed from femurs, and 4 × 10⁵ cells/well were plated in 1 ml DMEM/F12 (Invitrogen) supplemented with 1% FCS, 500 U/ml penicillin, 500 U/ml streptomycin and 10% monocyte-CSF-conditioned supplement from murine fibrosarcoma cell (L929) cultures (the concentrations of cortisol and cortisone in FCS at this concentration are below the limit of detection and <0.5 nM, respectively; below the Kₘ of the enzyme). Cells differentiated into macrophages over 7 d with medium changed every 3 d. Apolipoprotein AI (ApoAI)-mediated cholesterol efflux was measured in macrophages loaded with acetylated low-density lipoprotein (AcLDL) by incubation with 50 µg/ml [³H]-cholesterol-AcLDL for 24 h, then a further 24 h in the presence or absence of 10 µg/ml human ApoAI. [³H]-cholesterol was measured in centrifuged medium and in cells after lipids were extracted with hexane: isopropanol (3:2 v/v). Total cholesterol was measured on cellular lipids using an enzymatic assay (Boehringer, Ingelheim, Germany). The percentage of specific cholesterol efflux was calculated [medium cholesterol/(medium cholesterol + cellular cholesterol)] after subtraction of values for ApoAI-free medium.

**Statistics**

Values are expressed as means ± se. Statistical analysis was performed using Student’s t test, 1-way ANOVA, 2-way
ANOVA, or repeated-measures ANOVA, followed by Tukey
post hoc test, as appropriate. Values of $P < 0.05$ were consid-
ered statistically significant.

RESULTS

11β-HSD1 deficiency or inhibition attenuates
atherosclerosis in ApoE-KO mice

WD-fed ApoE-KO mice had extensive atherosclerotic les-
sions in the aortic arch and its major branches; narrowing
was most severe in the innominate artery (Fig. 1Ai). Innomi-
inate artery lesions in WD-fed ApoE-KO mice were
complex, with fibrous caps comprising smooth muscle, col-
lagen, and elastin overlying areas of lipid deposition with
evidence of cholesterol crystal formation (Fig. 1Aii–iv).
Administration of a selective 11β-HSD1 inhibitor to
WD-fed ApoE-KO mice for 8 wk reduced atheroscle-
rotic lesion size in all major (aortic arch, common
carotid, innominate) arterial territories examined (Fig.
1Ai). The maximum cross-sectional narrowing of the
innominate artery was significantly attenuated by 11β-
HSD1 inhibition (Fig. 1Bi). Interestingly, 11β-HSD1
inhibition for 8 wk improved markers of plaque stability
(Fig. 1Ci), with significantly more lesional collagen,
smaller areas devoid of cells or collagen (probably
reflecting extracellular lipid pools), and no increase in
smooth muscle cells (Fig. 1Ci).

The atheroprotective effects of 11β-HSD1 inhibitors

![Figure 4](image_url)

**Figure 4.** Effect of 11β-HSD1 deficiency on inflammatory monocytes ($7/4^{hi}$Ly6G$^+$CD11b$^+$) and neutrophils ($7/4$Ly6G$^+$CD11b$^+$) in blood, BM, and spleen. DKO and ApoE-KO mice (4 wk old) were fed chow diet or WD for 14 wk, and then monocyte and neutrophil numbers in the blood (A), BM (B), and spleen (C) were quantified by flow cytometric analysis ($n=5–21$/group). *$P < 0.05$, **$P < 0.01$ for effects of genotype; †$P < 0.05$ for effects of diet.
were recapitulated in genetic deficiency of 11β-HSD1, confirming on-target actions. Thus, in WD-fed DKO mice, the area of the innominate artery affected by atherosclerotic lesions was strikingly reduced compared to ApoE-KO controls (Fig. 2A, C). WD-fed 11β-HSD1⁻/⁻ (het) mice also had reduced atherosclerotic lesions at the innominate artery, showing that partial 11β-HSD1 deficiency is also protective against severe atherosclerosis (Fig. 2A). Reduced lesion size in het and DKO mice was accompanied by an increase in luminal area (Fig. 2A).

**Reduced lesion size with 11β-HSD1 deficiency is not due to improvements in metabolic cardiovascular risk factors or endothelial function**

Systemic risk factors contribute to atherosclerosis, and 11β-HSD1 inhibition/deletion reduces several of these (obesity, glucose intolerance, and dyslipidemia) in high-fat dietary obesity in mice (14–16) and humans with type 2 diabetes (17). However, although WD feeding caused modest weight gain, there were no major differences between DKO and ApoE-KO mice in food intake or body weight (Table 2); if anything, DKO mice were slightly heavier. Notably, 11β-HSD1 deficiency on the ApoE-KO background did not affect plasma cholesterol and triglyceride levels in chow-fed mice, or the marked elevation of cholesterol on WD, although the WD-induced elevation of plasma triglycerides was attenuated in DKO mice (Table 2). Moreover, short-term (8 wk) 11β-HSD1 inhibition in WD-fed ApoE-KO mice did not alter fasting plasma cholesterol, triglyceride, or NEFA levels (Table 3), while reduced lesion size in WD-fed 11β-HSD1 hets was associated with higher cholesterol (34.4 ± 2.5 mM) and triglyceride (2.90 ± 0.30 mM) levels. Thus, the development of smaller lesions in mice with 11β-HSD1 deletion or inhibition is independent of lipid lowering. Similarly, 11β-HSD1 inhibition did not affect fasting plasma glucose or insulin levels in ApoE-KO mice (Table 3), suggesting that the protection against lesion formation is not due to improved glycemia on this strain background and diet.

Endothelial dysfunction may contribute to atherosclerosis. Aortic rings from DKO mice and ApoE-KO controls, whether fed normal chow or WD, showed identical acetylcholine-elicited endothelium-dependent vasodilation (Table 4). There were also no differences by genotype or diet in SNP-mediated vasodilation (Table 4). Thus, changes in endothelial and vascular smooth muscle function do not underlie atheroprotection.

Circulating glucocorticoid excess may contribute to atherogenesis. However, basal plasma corticosterone levels were similar in ApoE-KO (42.8 ± 13.6 nM; n = 6) and DKO (50.6 ± 8.4 nM; n = 8) mice. As reported previously (14), adrenal glands were heavier (P < 0.001) in DKO (0.20 ± 0.01 mg/g body wt; n = 6) than ApoE-KO (0.14 ± 0.01 mg/g body weight; n = 7) mice, reflecting increased adrenal corticosterone production with 11β-reductase deficiency.

**11β-HSD1-deficiency modestly reduces inflammatory cell infiltration of atherosclerosis**

11β-HSD1, encoding an exclusive reductase, is expressed in innate (monocytes and macrophages; refs. 20, 21, 39) and adaptive (T cells; ref. 22) immune cells;
both are implicated in atherosclerosis (2, 5, 43). This enzyme activity was abolished in resident peritoneal cells (macrophages and neutrophils) from mice with 11β-HSD1 deletion (11β-reductase activity: wild-type, 7.7 pmol/h/10^6 cells; 11β-HSD1-KO, below the limit of detection of the assay, <0.2 pmol/h/10^6 cells). Although 11β-HSD1 deficiency causes worsening of acute inflammation in joints and peritoneum, there was no evidence of worse chronic inflammation in atherosclerotic plaques. Indeed, in DKO atherosclerotic plaques, macrophage numbers were reduced overall (if unaltered per lesion area; Fig. 3B, C), and there was a 36% reduction in CD3^+ T cells per lesion area (Fig. 3D, E). Real-time PCR detected iNOS (marker for M1), Relm-a (Fizz-1), and mannose receptor (markers for M2) in aortic lesions from ApoE^−/− and DKO mice, but there was no difference by genotype (not shown), suggesting no change in macrophage polarization with 11β-HSD1 deficiency in this context. Reduced inflammatory cells in atherosclerotic plaques could be due to reduced circulating cells. In ApoE-KO controls, WD caused monocytosis, a change associated with fewer monocytes in BM and spleen, suggesting release from these stores (Fig. 4A). In contrast, in DKO mice, the WD-induced monocytosis was attenuated and WD increased the number of monocytes in spleen and BM (Fig. 4B, C). Although circulating neutrophils were unaffected by diet or genotype, these cells were also increased by WD in the BM and spleen of DKO mice, again suggesting increased proliferation and/or retention (Fig. 4). Indeed, DKO mice exhibited splenomegaly following WD, while the spleen weights in ApoE-KO mice were not increased by WD (Table 2). However, despite reduced circulating monocytes in WD-fed DKO mice, the 7/4^hi CD11b^Ly6G^ (corresponding to Ly6C^hi^) subset that accumulates in ApoE-KO atherosclerotic plaques (44, 45) was similar in the blood and BM of chow-fed DKO mice, suggesting little difference in pathogenic cell numbers. Moreover, macrophages in chow-fed DKO and ApoE-KO mice were recruited similarly to the peritoneum following injection of thioglycollate (Fig. 5), confirming their ability to be recruited to sites of local inflammation.

MCP-1 is the major macrophage chemoattractant in atherosclerosis (46). On a chow diet, serum MCP-1 levels were similar in DKO and ApoE-KO mice (Fig. 6A). WD increased serum MCP-1 in ApoE-KO mice, but DKO mice resisted this rise (Fig. 6A), affording an explanation for the apparent retention of cells in DKO mouse BM and spleen. Reduced elaboration of MCP-1 in adipose tissue appeared to be responsible, at least in part, because mesenteric fat MCP-1 mRNA levels were reduced (Fig. 6B), whereas levels in liver were unaffected (data not shown). This was not a general change in adipose-derived chemokines since leptin mRNA did not differ (DKO, 1.27±0.38; ApoE-KO, 1.24±0.23 arbitrary units). Despite lower MCP-1 mRNA levels in DKO adipose tissue, aortic MCP-1 mRNA levels were elevated.

Figure 6. Effect of 11β-HSD1 deficiency on circulating MCP-1 and mesenteric adipose tissue MCP-1 mRNA expression and mRNA expression of MCP-1, CCR2, CX3CR1, and VCAM-1 in the ascending aortas. ApoE-KO and DKO mice (4 wk old) were fed chow diet or WD for 14 wk. A, B) Serum MCP-1 level (A) and MCP-1 mRNA expression levels in MesAT (B) were elevated by WD in ApoE-KO control mice, but not in DKO mice. C, D) Furthermore, although aortic MCP-1 (C), and CCR2 (D) mRNA levels were elevated by WD, there was no difference by genotype. E) CX3CR1 mRNA transcript levels in the aorta were unaltered by genotype and diet. F) Aortic VCAM-1 mRNA levels were similar in ApoE-KO and DKO mice fed chow diet. However, while WD increased VCAM-1 mRNA in ApoE-KO mice, there was no change in DKO tissue (n=5–8/group). *P<0.05, **P<0.01 for effects of genotype; †P<0.05, ††P<0.01 for effects of diet.
similarly by WD in DKO and control mice (Fig. 6C). MCP-1 acts largely via CCR2, but CCR2 mRNA levels in aorta were unaltered by genotype (Fig. 6D), as were aortic levels of mRNA encoding CX3CR1 (Fig. 6E), which is also key to monocyte chemotaxis into atherosclerotic lesions (42). Thus, differences in the local vascular MCP-1/chemokine receptor system do not appear to underpin reduced inflammatory cell infiltration in DKO atherosclerosis; rather this appears likely to be due, in part, to reduced availability of MCP-1.

Cell adhesion molecules, notably VCAM-1, are increased in atherosclerotic vessels and play a key role in mediating infiltration of both monocytes and lymphocytes into the vasculature (47). Aortic VCAM-1 mRNA levels were similar on Chow diet (Fig. 6F) but, while WD increased aortic VCAM-1 mRNA in ApoE-KO mice, this rise did not occur in DKO mice (Fig. 6F). This was specific to VCAM-1, since aortic ICAM-1 mRNA levels were unaffected by 11β-HSD1-deficiency or WD (data not shown). This suggests that, over and above any effects on inflammatory cell availability, the host vessel is less effective in recruiting inflammatory cells in 11β-HSD1 deficiency.

11β-HSD1 deficiency increases macrophage cholesterol efflux

Of course, 11β-HSD1-deficient macrophages in DKO atherosclerotic lesions might be more atherogenic, especially as high doses of glucocorticoids reduce macrophage cholesteryl ester hydrolysis and export (31), so relative glucocorticoid deficiency might be anticipated to promote cholesterol accumulation. However, uptake of AcLDL (Fig. 7A), or oxidized LDL (data not shown), was similar in 11β-HSD1-KO and wild-type macrophages, and 11β-HSD1 deficiency had no effect on expression of scavenger receptor A (SR-A) mRNA, the major mediator of cholesterol uptake (Fig. 7C), though 11β-HSD1-KO macrophages had modestly elevated levels of CD36 mRNA, which also mediates macrophage-cholesterol influx. In contrast, 11β-HSD1-KO macrophages showed greater ATP-binding cassette transporter A1 (ABCA1)-dependent cholesterol efflux (Fig. 7B), with significantly increased levels of mRNAs encoding the major cholesterol efflux transporters and acceptor, ABCA1, ATP-binding cassette transporter G1 (ABCG1), and ApoE. Thus, 11β-HSD1-deficient macrophages show an intrinsic antiatherosclerotic balance of cholesterol trafficking.

Atheroprotection occurs with 11β-HSD1−/− BM transplantation

To determine whether 11β-HSD1-deficient BM-derived cells are also intrinsically atheroprotective, ApoE-KO recipient mice were lethally irradiated, and BM was transplanted from either ApoE-KO or DKO mice. Following reconstitution, body and organ weights, plasma lipids, and circulating blood leukocyte numbers were not different between the groups, nor did hematopoietic 11β-HSD1 deficiency affect monocyte and neutrophil numbers in the BM and spleen (Table 5). However in ApoE-KO mice, innominate artery atherosclerotic lesion volume, assessed by OPT (38), and lesion cross-sectional area were significantly reduced by transplantation with DKO BM (Fig. 8), compared to lesions in ApoE-KO mice transplanted with autologous ApoE-KO BM. Macrophage infiltration into ApoE-KO atherosclerotic lesions was unaffected by deletion of 11β-HSD1 in BM cells (data not shown), similar to global 11β-HSD1-deficiency. Thus, atheroprotection is mediated by 11β-HSD1-deficient BM-derived cells.

DISCUSSION

11β-HSD1 deficiency or inhibition substantially reduces atherosclerosis in ApoE-KO mice. The effect was clearcut, was similar with short-term selective inhibition or genetic deficiency of 11β-HSD1, and involved both a...
Physiological glucocorticoids increase VCAM-1 plausibly due to lower circulating MCP-1 and less aortic cells and no increase in macrophages per lesional area, with $^{11}-HSD1$ and cholesterol export. Neutrophils (10^5 cells/femur) exhibit an atheroprotective phenotype of enhanced atheroprotection, plausibly at least in part because they exhibit high-affinity sites for corticosterone in the absence of high glucocorticoid receptor antagonists elevate VCAM-1 mRNA (51). Perhaps surprisingly, there was little alteration in circulating lipids to explain $^{11}-HSD1$ inhibition/deficiency also ameliorates a hyperlipidemic state of this strain and/or the only background. This may reflect the already markedly reduced atherosclerotic lesion size. Lethally irradiated ApoE-KO recipient mice were reconstituted with BM from ApoE-KO mice or DKO mice and fed WD for 12 wk. Formalin-fixed innominate arteries underwent OPT scanning. Analysis of lesion volumes ($A$) and lesion cross-sectional area ($B$) in the innominate arteries demonstrated that ApoE-KO recipient mice reconstituted with DKO BM cells exhibited significantly smaller lesions when compared to ApoE-KO mice reconstituted with ApoE-KO BM cells ($n=5/\text{group}$). *$P<0.05$, **$P<0.01$ vs. ApoE-KO BM $\rightarrow$ ApoE-KO.

**Figure 8.** $^{11}-HSD1$ deletion in BM cells reduces atherosclerotic lesion size. Lethally irradiated ApoE-KO recipient mice were reconstituted with BM from ApoE-KO mice or DKO mice and fed WD for 12 wk. Formalin-fixed innominate arteries underwent OPT scanning. Analysis of lesion volumes ($A$) and lesion cross-sectional area ($B$) in the innominate arteries demonstrated that ApoE-KO recipient mice reconstituted with DKO BM cells exhibited significantly smaller lesions when compared to ApoE-KO mice reconstituted with ApoE-KO BM cells ($n=5/\text{group}$). *$P<0.05$, **$P<0.01$ vs. ApoE-KO mice reconstituted with ApoE-KO BM cells.
11β-HSD1-deficient macrophages were able more efficiently to export cholesterol, an impact expected to be even greater when ApoE is present (ApoE mRNA levels were higher in 11β-HSD1-KO macrophages), since ApoE is a key atheroprotective VLDL cholesterol transporter with anti-inflammatory effects (52, 53). This suggests that 11β-HSD1 inhibitor-mediated atheroprotection may extend to models of atherosclerosis expressing ApoE and perhaps to humans. Notably, the atheroprotective effect was seen with 11β-HSD1 deficiency restricted in transplanted BM, implying a key role for 11β-HSD1-deficiency in BM-derived cells over and beyond any effects on host metabolism or the aortic milieu per se. Overall, this study localizes the atheroprotective effects of 11β-HSD1 deficiency/inhibition to 11β-HSD1 deficiency in BM. This is very likely to be mediated by leukocytes, e.g., changes in macrophages, but further work is required to characterize which BM-derived leukocytes are responsible. These results support the clinical development of selective inhibitors of 11β-HSD1 as a novel multimodal treatment for atherosclerosis and leisional inflammation over and above their role in metabolic disease, from which the major cause of mortality is atherosclerotic disease.

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REFERENCES


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