Repurposing dichloroacetate for the treatment of women with endometriosis

Citation for published version:

Digital Object Identifier (DOI):
10.1073/pnas.1916144116

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Publisher's PDF, also known as Version of record

Published In:
Proceedings of the National Academy of Sciences

General rights
Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.
Repurposing dichloroacetate for the treatment of women with endometriosis

Andrew W. Horne\textsuperscript{a,1,2}, S. Furqan Ahmad\textsuperscript{a,1}, Roderick Carter\textsuperscript{b}, Ioannis Simitsidellis\textsuperscript{c}, Erin Greaves\textsuperscript{a}, Chloe Hogg\textsuperscript{a}, Nicholas M. Morton\textsuperscript{b}, and Philippa T. K. Saunders\textsuperscript{a}

\textsuperscript{a}Medical Research Council Centre for Reproductive Health, The University of Edinburgh, Edinburgh EH16 4TJ, United Kingdom; \textsuperscript{b}British Heart Foundation Centre for Cardiovascular Science, The University of Edinburgh, Edinburgh EH16 4TJ, United Kingdom; and \textsuperscript{c}Centre for Inflammation Research, The University of Edinburgh, Edinburgh EH16 4TJ, United Kingdom

Edited by David J. Mangelsdorf, The University of Texas Southwestern Medical Center, Dallas, TX, and approved November 13, 2019 (received for review September 17, 2019)

Endometriosis is a chronic pain condition affecting \sim 176 million women worldwide. It is defined by the presence of endometrium-like tissue (lesions) outside the uterus, most commonly on the pelvic peritoneum. There is no cure for endometriosis. All endometriosis drug approvals to date have been contraceptive, limiting their use in women of childbearing age. We have shown that human peritoneal mesothelial cells (HPMCs) recovered from the pelvic peritoneum of women with endometriosis exhibit significantly higher glycolysis, lower mitochondrial respiration, decreased enzymatic activity of pyruvate dehydrogenase (PDH), and increased production of lactate compared to HPMCs from women without disease. Transforming growth factor-\(\beta\) (TGF-\(\beta\)) is elevated in the peritoneal fluid from women with endometriosis, and exposure of HPMCs to TGF-\(\beta\) exacerbates this abnormal phenotype. Treatment of endometriosis HPMCs with the pyruvate dehydrogenase kinase (PDK) inhibitor/PDH activator dichloroacetate (DCA) normalizes HPMC metabolism, reduces lactate secretion, and abrogates endometrial stromal cell proliferation in a coculture model. Oral DCA reduced peritoneal fluid lactate concentrations and endometriosis lesion size in a mouse model. These findings provide the rationale for targeting metabolic processes as a noncontraceptive treatment for women with endometriosis either as a primary nonhormonal treatment or to prevent recurrence after surgery.

Results
Peritoneal Mesothelial Cells from Women with Endometriosis Have a Glycolytic Phenotype. We documented higher levels of basal glycolysis (\(P = 0.0499\)), lower mitochondrial respiration (ATP-linked) (\(P = 0.0400\)), and higher lactate secretion (\(P = 0.0004\)) in HPMCs from women with endometriosis compared to women without disease (Fig. 1 A–C). “Endo” HPMCs exhibited decreased enzymatic activity of pyruvate dehydrogenase (\(P = 0.0025\)) (Fig. 1D).

DCA Corrected the Glycolytic Phenotype of Peritoneal Mesothelial Cells from Women with Endometriosis and Decreased Stromal Cell Proliferation In Vitro. Treatment of Endo HPMCs with DCA normalized their metabolic phenotype and increased PDH activity, in the presence or absence of TGF-\(\beta\) (Fig. 1 E–H). In a coculture system (Fig. 1J), treatment of endometriosis HPMCs with DCA decreased basal and TGF-\(\beta\)-stimulated HPMC lactate secretion (\(P = 0.0003\)) and proliferation of endometrial stromal cells (\(P = 0.0002\), Fig. 1 J and K).

Discussion
HPMCs from women with endometriosis synthesize and secrete more lactate than cells recovered from women without lesions. Lactate can stimulate cell migration and invasion, and immune escape during tumorigenesis, with the same processes implicated in the etiology of endometriosis (2). We postulate that increased lactate concentrations in pelvic PF may create an environment that promotes invasion of ectopic endometrial cells into the peritoneum so that they form lesions.

We have shown that Endo HPMCs exhibit a greater dependence on energy production through glycolysis under aerobic conditions than those of women who are disease-free. This abnormal cellular energy state is corrected by treatment with the small-molecule drug DCA. Notably, DCA reduced HPMC lactate release in vitro, and oral dosing of mice reduced endometriosis lesion size in vivo. DCA is a pyruvate dehydrogenase kinase (PDK) inhibitor used to treat cancer (5). Four different isoforms of PDK (PDK1–4) exist with variable expression reported: PDK1 appears to have the highest sensitivity to inhibition by DCA (6). PDK inhibition reduces phosphorylation of PDH, increasing PDH activity leading to lower release of metabolites such as lactate. DCA also inhibits...
proliferative and proangiogenic transcription factors such as HIF-1α (5). In a clinical trial in patients with glioblastoma, DCA decreased tumor growth and angiogenesis (7).

While we have focused on HPMCs, an overlooked source of metabolic factors in PF, DCA could also have an impact on other cell types altered in endometriosis patients. Macrophages that are present in PF or lesions of women with endometriosis exhibit a range of phenotypes (8), and treatment with DCA could drive metabolic reprogramming of macrophages toward a prorepair phenotype that could have a positive impact on the pathogenesis of the disease (9). Stromal cells in patient endometrium and lesions exhibit up-regulation of PDK1. If apoptosis of these cells is enhanced by DCA (10), this could contribute to reduced lesion growth.

To translate these results to women, we are using DCA in an exploratory-phase clinical trial (ClinicalTrials.gov identifier NCT04046081). If effectiveness and acceptability are demonstrated, DCA would be a nonhormonal treatment for women with this debilitating condition.

**Methods**

**Human Cell Culture.** Approval was obtained from the Lothian Research Ethics Committee (LREC 11/AL/0376). Samples were collected from women attending a pain clinic who had a diagnosis of peritoneal endometriosis (Endo group) or women without macroscopic evidence of endometriosis at laparoscopy (“No Endo” group), all of whom had given informed consent. Women were not on hormones and had regular menstrual cycles. HPMCs were cultured in HOSE I media (40% Media 199, 40% IMDM, 15% heat-inactivated FBS, 0.5% penicillin/streptomycin, and 1% L-glutamine). All
cell/tissue samples were deidentified (anonymized but linked) prior to use in the study. Immortalized human endometrial stromal cells [SHT290 (11)] were grown in RPMI 1640 media plus 10% heat-inactivated FBS, 1% penicillin/Streptomycin, 1% l-glutamine, and 1% nonessential amino acids. Cells were incubated at 37 °C under 5% CO2 in air.

Seahorse Analysis. Extracellular acidification rate (ECAR) and oxygen consumption rate (OCR) were determined using a glycolytic stress test kit (102340-100; Agilent) on a Seahorse XFe24 Analyzer. HPMCs were seeded in microplates at a density of 2 x 10^4 cells per well in 500 μL of HOSE I and incubated for 48 h. Cells were rinsed 3 times with 500 μL of prewarmed Seahorse Assay DMEM (no glucose or pyruvate); 525 μL of same medium was added to wells that were incubated at 37 °C for 30 min. ECAR and OCR measurements were taken simultaneously using an 8-min protocol (3-min mixing, 2-min wait, 3-min measure). 12 measurements were taken from each well; 3 times baseline prior to injection of glucose (10 mM), 3 following glucose and prior to injection of oligomycin (1 μM), 3 following oligomycin and prior to injection of 2-deoxyglucose (100 mM), and 3 following injection of 2-deoxyglucose. Basal glycolysis was calculated by subtracting the average ECARs before, and after, the injection of glucose. ATP-linked mitochondrial respiration was calculated by subtracting the average OCRs before and after the injection of oligomycin. After assay, cells were washed with PBS and protein was quantified to for normalization. Additional experiments used Endo HPMCs cultured for 16 h in HOSE 1, then switched to serum-free HOSE 1 containing vehicle (water), DCA (15 mM), TGF-β1 (2 ng/mL), or TGF-β1+DCA for 48 h. Lactate concentrations were measured, and proliferation of SHT290 cells was determined using CellTitre96 Aqueous-one solution reagent (G3580; Promega).

Mouse Model of Endometriosis. Animal procedures were performed in accordance with UK Home Office regulations (license 70/8945). A preclinical model of endometriosis was as in ref. 4 with the minor modification that recipient mice were not ovariectomized or treated with E2. After 2 wk, mice were randomly assigned to receive vehicle (water) or DCA (100 mg/kg) daily via oral gavage for 7 d (n = 10/group). PF was recovered by lavage (2 mL of ice-cold PBS); endometriosis lesions were fixed in 4% neutral-buffered formalin, lactate was measured in PF, sections of lesions were stained with H&E, and the area was measured using ImageJ software.

Lactate and PDH Activity. Lactate concentrations were determined using an enzymatic colorimetric kit (Alpha Laboratories) on a Cobas Fara centrifugal analyzer (Roche Diagnostic). PDH enzyme activity was measured using a Dipstick assay kit (ab109882; Abcam): band intensity was analyzed using ImageJ.


Horne et al.