Bedaquiline, an FDA-approved antibiotic, inhibits mitochondrial function and potently blocks the proliferative expansion of stem-like cancer cells (CSCs)


10.18632/aging.100983

<table>
<thead>
<tr>
<th>Title</th>
<th>Bedaquiline, an FDA-approved antibiotic, inhibits mitochondrial function and potently blocks the proliferative expansion of stem-like cancer cells (CSCs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Authors</td>
<td>Fiorillo, M, Lamb, R, Tanowitz, H, Cappello, A, Martinez-Outschoorn, U, Sotgia, Federica and Lisanti, MP</td>
</tr>
<tr>
<td>Type</td>
<td>Article</td>
</tr>
<tr>
<td>URL</td>
<td>This version is available at: <a href="http://usir.salford.ac.uk/39196/">http://usir.salford.ac.uk/39196/</a></td>
</tr>
<tr>
<td>Published Date</td>
<td>2016</td>
</tr>
</tbody>
</table>

USIR is a digital collection of the research output of the University of Salford. Where copyright permits, full text material held in the repository is made freely available online and can be read, downloaded and copied for non-commercial private study or research purposes. Please check the manuscript for any further copyright restrictions.

For more information, including our policy and submission procedure, please contact the Repository Team at: usir@salford.ac.uk.
Bedaquiline, an FDA-approved antibiotic, inhibits mitochondrial function and potently blocks the proliferative expansion of stem-like cancer cells (CSCs)

Marco Fiorillo¹²³, Rebecca Lamb¹², Herbert B. Tanowitz⁴, Anna Rita Cappello³, Ubaldo E. Martinez-Outschoorn⁵, Federica Sotgia⁶, and Michael P. Lisanti¹²

¹The Breast Cancer Now Research Unit, Institute of Cancer Sciences, Cancer Research UK Manchester Institute, University of Manchester, Manchester, UK
²The Manchester Centre for Cellular Metabolism (MCCM), Institute of Cancer Sciences, Cancer Research UK Manchester Institute, University of Manchester, Manchester, UK
³The Department of Pharmacy, Health and Nutritional Sciences, The University of Calabria, Cosenza, Italy
⁴Departments of Pathology and Medicine, Albert Einstein College of Medicine, Bronx, NY 10461, USA
⁵The Sidney Kimmel Cancer Center, Philadelphia, PA 19107, USA
⁶School of Environment & Life Sciences, Cockcroft Building, University of Salford, Salford, UK

Key words: bedaquiline, mitochondria; tumor-initiating cells (TICs), cancer stem-like cells (CSCs), drug repurposing

Received: 05/07/16; Accepted: 06/06/16; Published: 06/22/16
Correspondence to: Michael P. Lisanti, PhD; Federica Sotgia, PhD; E-mail: michaelplisanti@gmail.com; fsotgia@gmail.com

Abstract: Bedaquiline (a.k.a., Sirturo) is an anti-microbial agent, which is approved by the FDA for the treatment of multi-drug resistant pulmonary tuberculosis (TB). Bedaquiline is a first-in-class diarylquinoline compound, that mechanistically inhibits the bacterial ATP-synthase, and shows potent activity against both drug-sensitive and drug-resistant TB. Interestingly, eukaryotic mitochondria originally evolved from engulfed aerobic bacteria. Thus, we hypothesized that, in mammalian cells, bedaquiline might also target the mitochondrial ATP-synthase, leading to mitochondrial dysfunction and ATP depletion. Here, we show that bedaquiline has anti-cancer activity, directed against Cancer Stem-like Cells (CSCs). More specifically, we demonstrate that bedaquiline treatment of MCF7 breast cancer cells inhibits mitochondrial oxygen-consumption, as well as glycolysis, but induces oxidative stress. Importantly, bedaquiline significantly blocks the propagation and expansion of MCF7-derived CSCs, with an IC-50 of approx. 1-μM, as determined using the mammosphere assay. Similarly, bedaquiline also reduces both the CD44+/CD24low/- CSC and ALDH+ CSC populations, under anchorage-independent growth conditions. In striking contrast, bedaquiline significantly increases oxygen consumption in normal human fibroblasts, consistent with the fact that it is well-tolerated in patients treated for TB infections. As such, future pre-clinical studies and human clinical trials in cancer patients may be warranted. Interestingly, we also highlight that bedaquiline shares certain structural similarities with trans-piceatannol and trans-resveratrol, which are known natural flavonoid inhibitors of the mitochondrial ATP-synthase (complex V) and show anti-aging properties.

INTRODUCTION

Residual treatment-resistant cancer cells are thought to be the drivers of poor clinical outcomes, in many cancer types [1]. These tumor-initiating cells (TICs) or cancer stem-like cells (CSCs) are resistant to conventional therapies, leading to recurrence, metastatic cell dissemination and drug-resistance [2-4]. CSCs are resistant to cellular stress, and are able to undergo anchorage-independent growth, allowing the formation of 3D multi-cellular tumor spheroids, that share properties with CSCs and progenitor cells [5, 6]. During
these anchorage-independent conditions, most “bulk” epithelial cancer cells undergo cell death, termed “anoikis”. Thus, each 3D multi-cellular tumor-sphere is formed from the clonal expansion of a single CSC. As such, 3D tumor sphere formation enriches for a cell population with CSC-like properties [6]. In this context, 3D tumor spheres (i.e., mammospheres) prepared from breast cancer epithelial cell lines are a well-established model system.

We and others have recently shown that CSCs are critically dependent on mitochondrial function, for their successful propagation and clonal expansion [7-11]. In fact, during mammosphere formation, five subunits of the mitochondrial ATP synthase are significantly up-regulated (ATP5B, ATP5A1, ATP5F1, ATP5H and ATP5O); remarkably, ATP5B was dramatically over-expressed in MCF7-derived mammospheres, as compared with MCF7 monolayer cells [7]. Clinically, ATP5B protein levels are also elevated in the serum of patients with breast cancer and ATP5B is part of a 21-protein signature that predicts the development of distant metastasis [12].

During our continued search for FDA-approved drugs that may behave as mitochondrial inhibitors, we identified bedaquiline, an antibiotic that was originally developed to block the bacterial ATP-synthase of multi-drug resistant pulmonary tuberculosis (TB) [13-15]. Because mitochondria originally evolved from bacteria, we speculated that bedaquiline might also target the mitochondrial ATP-synthase (Complex V), leading to ATP depletion.

Here, we propose that bedaquiline could be repurposed as a new anti-cancer drug, for the targeting in mitochondria within CSCs. More specifically, we show that bedaquiline treatment of MCF7 breast cancer cells inhibits oxygen-consumption and metabolically induces aerobic glycolysis (the Warburg effect), as well as oxidative stress. Importantly, bedaquiline blocks the propagation of MCF7-derived CSCs, with an IC-50 of 1 μM, as determined using the mammosphere assay. Bedaquiline also targets both CD44+/CD24low/- CSC and ALDH+ CSC populations, under anchorage-independent growth conditions.

RESULTS

Here, we aimed to assess the mitochondrial inhibitory effects of bedaquiline (also known as TMC207 and R207910). In addition, we tested the hypothesis that bedaquiline could be used to inhibit the propagation of CSCs. The structure of bedaquiline is shown in Figure 1.

Metabolic profiling of MCF7 breast cancer cells treated with bedaquiline

First, we investigated the metabolic effects of bedaquiline on MCF7 breast cancer cells grown as monolayers. Extracellular acidification rates (ECAR) and real-time oxygen consumption rates (OCR) for cells treated with bedaquiline were assessed using the Seahorse Extracellular Flux (XFe-96) analyzer. More specifically, OCR is a surrogate marker for OXPHOS activity, while ECAR is a measure of glycolysis.

Figure 2 shows that bedaquiline dose dependently inhibits oxygen consumption in MCF7 cells, reducing respiration, both maximal and basal, as well as ATP levels. In addition, bedaquiline inhibited glycolysis in MCF7 cells (Figure 3, A-E). Determination of the Cell Energy Profile indicated that bedaquiline shifts MCF7 cells from an energetic to a quiescent state (Figure 3F).

Next, we performed FACS analysis on MCF7 cells stained with MitoTracker probes to follow mitochondrial mass and membrane potential. Figure 4A shows that bedaquiline reduces MitoTracker Orange staining, indicative of decreased mitochondrial membrane potential. Conversely, Figure 4B shows that bedaquiline increases MitoTracker Deep-Red staining, reflecting increased mitochondrial mass. Importantly, assessing the ratio of mitochondrial membrane potential to mass revealed that bedaquiline significantly reduces membrane potential per mitochondria (Figure 4C). Finally, Reactive Oxygen Species (ROS) levels were
increased, as assessed by FACS analysis using the CM-H$_2$DCFDA probe (Figure 4D). In summary, these data provide direct evidence that bedaquiline functionally targets mitochondria by inhibiting oxygen consumption in human breast cancer cells, driving an increase in oxidative stress and glycolytic function.

**Figure 2.** Bedaquiline greatly diminishes oxygen consumption in MCF7 breast cancer cells. The Seahorse XF96 analyzer was employed to determine the mitochondrial function of MCF7 cells treated with bedaquiline (1μM and 10 μM) for 48 hours. (A) A line graph of 3 independent experiments is shown. (B, C, D) Respiration (basal and maximal), as well as ATP levels, were significantly decreased. *** p<0.0001, **** p<0.00001.

**Table 1.** High ATP5B mRNA levels are associated with decreased overall survival, in both ER(+) and ER(-) breast cancer patients.

<table>
<thead>
<tr>
<th>Cancer Subtype</th>
<th>HR/OS</th>
<th>Log-Rank</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Subtypes</td>
<td>1.64</td>
<td>8.3e-05</td>
<td>1,103</td>
</tr>
<tr>
<td>ER(+)</td>
<td>1.77</td>
<td>7.4e-05</td>
<td>819</td>
</tr>
<tr>
<td>ER(-)/Basal</td>
<td>2.41</td>
<td>0.019</td>
<td>198</td>
</tr>
<tr>
<td>ER(+)/Luminal A</td>
<td>1.63</td>
<td>0.039</td>
<td>500</td>
</tr>
<tr>
<td>ER(+)/Luminal B</td>
<td>1.98</td>
<td>0.001</td>
<td>319</td>
</tr>
</tbody>
</table>

ER, estrogen receptor; HR, hazard ratio; OS, overall survival; N, the number of patients in a given subtype or group. Overall survival data spans from 15-20 years post-diagnosis.
Metabolic profiling of normal human fibroblasts (hTERT-BJ1) treated with bedaquiline

To assess whether bedaquiline also behaves as a mitochondrial inhibitor in normal human fibroblasts, we examined its metabolic effects on hTERT-BJ1 cells, after 48 hours treatment. Interestingly, Figure 5 demonstrates that bedaquiline augments oxygen consumption and ATP levels in normal human fibroblasts, as determined by using the Seahorse XF-e96 analyzer. In addition, bedaquiline also boosts glycolysis in normal human fibroblasts, as seen in Figure 6. Remarkably, the Cell Energy Profile plot (OCR versus ECAR) shows that bedaquiline shifts normal human fibroblasts from a quiescent to an energetic state (Figure 6F), improving their overall metabolic profile. Thus, our results firmly establish that bedaquiline specifically inhibits mitochondrial respiration in cancer cells, while enhancing mitochondrial function in normal cells.
Bedaquiline significantly inhibits CSC propagation and survival

Since bedaquiline behaved as a specific inhibitor of mitochondrial respiration in cancer cells, we next examined its effects on the behavior of the CSC population.

More specifically, MCF7 cells were grown as mammospheres and treated with bedaquiline at increasing concentrations. Vehicle alone controls were processed in parallel. Interestingly, Figure 7A shows that bedaquiline halts mammosphere formation in a dose-dependent fashion (IC-50 ~1 μM). In addition, expression levels of CSC markers (CD24 and CD44) under these anchorage-independent conditions, bedaquiline diminished the CD44+/CD24-low cancer cell population, which are believed to be the tumor-initiating cells (Figure 7B).

Finally, we evaluated the levels of ALDEFLUOR, an independent marker of CSCs. ALDEFLUOR was measured by FACS analysis. Figure 7C shows that bedaquiline significantly decreases the ALDEFLUOR-positive cell population. As a negative control, we employed DEAB (diethylaminobenzaldehyde), a specific ALDH inhibitor (Figure 7D). Thus, these results indicate that bedaquiline pre-treatment reduces the CSC population, as assessed by three independent parameters, namely mammosphere formation, CD44/CD24 staining and ALDEFLUOR activity.

Bedaquiline does not affect the viability of the total cancer cell population, or normal human fibroblasts

We next determined if bedaquiline targets only the CSC-population, or if bedaquiline generally reduces the survival of the ‘bulk’ MCF7 cancer cell population and/or normal human fibroblasts (hTERT-BJ1). Figure

www.impactaging.com 5 AGING, June 2016, Vol. 8 No.6
8A shows that bedaquiline treatment had little or no effect on MCF7 cell viability, even at a concentration of 10 μM. Similarly, bedaquiline treatment had no effect on the viability of normal human fibroblasts (Figure 8B). In summary, our results indicate that bedaquiline preferentially inhibits the CSC population (compare Figures 7 and 8), relative to the ‘bulk’ cancer cells and fibroblasts.

**Validation of the prognostic value of ATP5B in human breast cancer patients, in both ER(+) and ER(-) sub-types**

Clinically, ATP5B protein levels are elevated in the serum of patients with breast cancer and ATP5B is part of a 21-protein signature that predicts the development of distant metastasis [12]. Here, we further validated the prognostic value of ATP5B. More specifically, we assessed whether the levels of ATP5B mRNA show any prognostic value in human breast cancer patient cohorts, with long-term follow-up (approaching 15-20 years). Results are summarized in Table 1. High mRNA expression levels of ATP5B were clinically associated with significantly reduced overall survival. Similar results were obtained in both ER(+) and ER(-) patients, as well as in ER(+) sub-types (Table 1). For specific Kaplan-Meier (K-M) curves, please see Supplemental Figure S1. Thus, we independently confirmed the prognostic value of ATP5B, a key subunit of mitochondrial complex V. As such, elevated levels of ATP5B could possibly be used to identify breast cancer patients that might benefit from treatment with bedaquiline.

**Figure 5. Bedaquiline augments oxygen consumption in normal human fibroblasts.** The Seahorse XF96 analyzer was employed to determine the mitochondrial function of MCF7 cells treated with 10 μM bedaquiline for 48 hours. (A) The line graph of 3 independent experiments is shown. (B, C, D) Basal respiration, maximal respiration, and ATP levels were all increased by bedaquiline treatment of normal fibroblasts. ** p<0.001.
DISCUSSION

Bedaquiline is an FDA-approved anti-microbial drug that was developed by Janssen Pharmaceuticals for the treatment of multi-drug resistant pulmonary tuberculosis (TB) [14]. It was first approved by the FDA at the end of 2012. Bedaquiline mechanistically inhibits the bacterial ATP synthase [13]. Thus, we hypothesized that, in cancer cells, bedaquiline might also target the mitochondrial ATP-synthase, leading to mitochondrial dysfunction and ATP depletion. Here, we explored the possibility that bedaquiline could be repurposed for

Figure 6. Bedaquiline augments glycolysis in normal human fibroblasts. The Seahorse XF96 analyzer was employed to determine the status of glycolysis in normal human fibroblasts treated with 10μM bedaquiline for 48 hours. (A) The line graph of 3 independent experiments is shown. (B, C, D, E) Glycolysis, glycolytic reserve, and ECAR were elevated. F. The plot of OCR versus ECAR shows that bedaquiline shifts the metabolic state of normal fibroblasts from a quiescent state to an energetic state. ** p<0.001.
targeting mitochondrial complex V in breast cancer cells. To test this hypothesis, we determined its metabolic effects on MCF7 cells, using the Seahorse XF-e96, to measure mitochondrial function and glycolysis. Our results demonstrate that bedaquiline dramatically inhibits oxygen consumption and ATP production in the low micromolar range. In addition, bedaquiline treatment also reduced aerobic glycolysis (a.k.a., the Warburg effect). In this context, bedaquiline reduced mitochondrial membrane potential, but increased mitochondrial mass and overall ROS production. Most importantly, bedaquiline potently inhibited the propagation of CSCs, with an IC-50 of 1 μM, as measured using the mammosphere assay. Remarkably, bedaquiline treatment increased mitochondrial respiratory function, ATP production, and glycolysis in normal human fibroblasts. Thus, these results provide clear evidence that bedaquiline specifically inhibits mitochondrial respiration in MCF7 cancer cells, but not in normal human fibroblasts. As such, our new findings suggest that bedaquiline could be used to target the mitochondrial F0F1-ATPase/ATP synthase in CSCs.

Consistent with our current findings, we have previously shown that oligomycin, an established inhibitor of the mitochondrial ATP-synthase (complex V), effectively targets MCF7-derived CSCs with an IC-50 of 100 nM [7]. However, oligomycin (another antibiotic) in not FDA-approved, and is considered to be both a bacterial and mitochondrial “poison”, that is too toxic for safe use in humans or animals.

Interestingly, only one previous study showed that TMC207 (now known as bedaquiline) had little or no effect on ATP production in a human ovarian cancer cell line, namely OVCAR3 cells, with an IC-50 > 200 μM [16]. However, no other cancer cell lines were studied. Similarly to our results, bedaquiline had minimal inhibitory activity on oxygen consumption in mouse liver and bovine heart mitochondria. The authors thus suggested that the inhibitory effects of bedaquiline were restricted to mycobacterium. Importantly, the effects of bedaquiline on cancer stem-like cells were not evaluated [16]. It has been suggested that bedaquiline binds to the subunit C of the mycobacterial ATP synthase, based on computational modeling [17]. This corresponds to the three human genes, namely ATP5G1, ATP5G2, ATP5G3, which differ only in their mitochondrial import sequence, but not in the sequence of the mature protein.

Figure 7. Bedaquiline halts the propagation of the CSC population. (A) MCF7 cells were grown as mammospheres, and treated with bedaquiline at increasing concentrations or vehicle alone. Note that bedaquiline inhibits mammosphere formation efficiency (MFE), in a dose-dependent fashion, with an IC-50 of ~1 μM. * p<0.05, ** p< 0.01, evaluated by Student’s t test. (B) MCF7 cell monolayers were treated with bedaquiline (5μM and 10 μM) for 48 hours and then re-plated on low-attachment plates in the absence of bedaquiline for 12 hours. The expression of CD44 and CD24 (CSC markers) was analyzed by FACS. Note that the CD44(+)high/CD24(-)low cell population, which is believed to be the CSC population, is reduced by bedaquiline.
Interestingly, several natural products, especially polyphenolic phytochemicals [18], also act as inhibitors of the F0F1-ATPase/ATP synthase (Complex V), that is present within the inner membrane of eukaryotic mitochondria. These include the following compounds, listed in rank order of their potency: piceatannol > resveratrol > epigallocatechin-gallate > epicatechin-gallate/curcumin > genistein/biochanin A/ quercetin / kaempferol / morin > phloretin/ apigenin/daidzein.

Figure 7. Bedaquiline halts the propagation of the CSC population. (C, D) Similar results were also obtained using ALDEFLUOR as a marker of CSCs. ALDEFLUOR was measured by FACS analysis. DEAB (diethylaminobenzaldehyde), a specific ALDH inhibitor, was used as a negative control for each sample. **** p<0.00001.

Figure 8. Bedaquiline has little or no effect on the viability of MCF7 cancer cells and normal human fibroblasts. Bedaquiline (5μM and 10 μM) treatment of MCF7 cells and hTERT-BJ1 normal human fibroblasts was carried out for 5 days. The SRB assay was performed as a measure of cell viability. (A, B) Bedaquiline has little or no inhibitory effects on the viability of MCF7 cells and human fibroblasts. **** p<0.00001, ns not significant.
Figure 9. Bedaquiline does not stimulate a stress-response in normal fibroblasts. (A, B) Luc-reporter fibroblasts were employed to assess HIF and NFκB activation. Cells treated with 10 μM bedaquiline or DMSO control for 48 hours were analyzed by luciferase assays. Luminescence was normalized by SRB (total proteins). Bedaquiline does not activate NFκB pathway (A) in normal fibroblasts, while slightly reducing HIF activation (B) ** p<0.001, ns not significant.

Figure 10. Structure of trans-Piceatannol and trans-Resveratrol. (A) Interestingly, these polyphenolic phytochemicals act as inhibitors of the F0F1-ATPase/ATP synthase (Complex V), that is present within the inner membrane of eukaryotic mitochondria. These compounds have been suggested to act as either anti-cancer agents or as compounds that have anti-aging properties. (B) Structural similarities with the bedaquiline molecule are highlighted in orange. Note that the structural backbone of trans-piceatannol and trans-resveratrol is actually embedded within bedaquiline.
The structures of some of these compounds are highlighted in Figure 10A. Many of these flavonoid compounds have been suggested to act as either anti-cancer agents or as compounds that have anti-aging properties, consistent with their effects of reducing or “fine-tuning” mitochondrial function [18, 19].

Interestingly, Figure 10B shows that the structural backbone of trans-piceatannol and trans-resveratrol is actually embedded within bedaquiline. These common structural similarities within the bedaquiline molecule are specifically highlighted in orange. In fact, trans-piceatannol and trans-resveratrol also functionally demonstrate anti-bacterial properties, behaving as antibiotics [19].

Our overall approach to drug repurposing is briefly summarized in Figure 11. Thus far, we have identified six different classes of FDA-approved antibiotics that could be used to therapeutically target mitochondria in CSCs. As of yet, we do not know the underlying mechanism(s) of selectivity that allows the inhibitory effects of bedaquiline to be seen preferentially at the level of the CSC, but not in normal fibroblasts and to a lesser extend in mature cancer cells. One possibility is that the mitochondrial ATPase (Complex V) in cancer cells and CSCs undergoes a conformational change, so that its 3-D structure more closely resembles the ancient bacterial ATPase. This hypothesis deserves further investigation.

MATERIALS AND METHODS

Materials. MCF7 breast cancer cell lines were purchased from the ATCC. Human immortalized fibroblasts (hTERT-BJ1) were originally purchased from Clontech, Inc. Cells were cultured in Dulbecco’s modified Eagle’s medium (DMEM), supplemented with 10% FBS (fetal bovine serum), 2 mM GlutaMAX, and 1% Pen-Strep in a 37°C humidified atmosphere containing 5% CO₂, unless otherwise noted. Gibco-brand cell culture media (DMEM/F12) was purchased.
Seahorse XFe-96 metabolic flux analysis. Extracellular acidification rates (ECAR) and real-time oxygen consumption rates (OCR) for cells treated with bedaquiline were assessed using the Seahorse Extracellular Flux (XFe-96) analyzer (Seahorse Bioscience, MA, USA) [20]. 10,000 cells per well were seeded into XFe-96 well cell culture plates, and incubated overnight to allow attachment. Cells were then treated with bedaquiline (1 μM or 10 μM) for 48 hours. Vehicle alone (DMSO) control cells were processed in parallel. After 48 hours, cells were washed in PBS, harvested, and re-suspended in 300 μL of PBS/CM. Cells were then analyzed by flow cytometry using the Fortessa (BD Bioscience). ROS levels were estimated by using the mean fluorescent intensity of the viable cell population. The results were analyzed using FlowJo software (Tree star Inc.).

Mammosphere culture. A single cell suspension was prepared using enzymatic (1x Trypsin-EDTA, Sigma Aldrich, #T3924), and manual disaggregation (25 gauge needle) to create a single cell suspension [6]. Cells were plated at a density of 500 cells/cm² in mammosphere medium (DMEM-F12/B27/20ng/ml EGF/PenStrep) in non-adherent conditions, in culture dishes coated with (2-hydroxyethylmethacrylate) (poly-HEMA, Sigma, #P3932). Then, cells were treated with increasing concentrations of bedaquiline (range 1 μM to 25 μM). Vehicle alone (DMSO) control cells were processed in parallel. Cells were grown for 5 days and maintained in a humidified incubator at 37°C. After 5 days for culture, spheres >50 μm were counted using an eye piece graticule, and the percentage of cells plated which formed spheres was calculated and is referred to as percentage mammosphere formation, and was normalized to one (1 = 100 %MFE). Similar results were also obtained when cells were seeded at a density of 200 cells/cm².

CD44/CD24 analysis. 1 x 10⁵ MCF7 cells were treated with bedaquiline (5 μM and 10 μM) for 48 hours in 6-well plates, grown as a monolayer. Then, cells were trypsinized and seeded in low-attachment plates in mammosphere media. After 12 hours, MCF7 cells were spun down and incubated with CD24 (IOTest CD24-PE, Beckman Coulter) and CD44 (APC mouse Anti-Human CD44, BD Pharmingen cat.559942) antibodies for 15 minutes on ice. Cells were rinsed twice and incubated with LIVE/DEAD dye (Fixable Dead Violet reactive dye; Invitrogen) for 10 minutes. Samples were then analyzed by FACS (Fortessa, BD Bioscience). Only the live population, as identified by the LIVE/DEAD dye staining, was analyzed for CD24/CD44 expression. Data were analyzed using FlowJo software.

ROS staining. Reactive oxygen species (ROS) production was measured using CM-H₂DCFDA (C6827, Invitrogen), a cell-permeable probe that is non-fluorescent until oxidation within the cell. MCF7 cells were treated with 10 μM bedaquiline for 48 hours. Vehicle alone (DMSO) control cells were processed in parallel. After 48 hours, cells were washed with PBS, and incubated with CM-H₂DCFDA (diluted in PBS/CM to a final concentration of 1 μM) for 20 minutes at 37°C. All subsequent steps were performed in the dark. Cells were rinsed, harvested, and re-suspended in PBS/CM. Cells were then analyzed by flow cytometry using the Fortessa (BD Bioscience). ROS levels were estimated by using the mean fluorescent intensity of the viable cell population. The results were analyzed using FlowJo software (Tree star Inc.).
well plates, cells were fixed with 10% trichloroacetic acid (TCA) for 1 hour in cold room, and dried overnight at room temperature. Then, cells were incubated with SRB for 15 min, washed twice with 1% acetic acid, and air dried for at least 1 hour. Finally, the protein-bound dye was dissolved in 10 mM Tris pH 8.8 solution and read using a plate reader at 540 nm.

Evaluation of HIF and NFκB signaling pathways. The Cignal Lenti reporter assay (Luc) system (Qiagen) was chosen for monitoring HIF- and NFκB-Luc pathway activity in fibroblasts, as we previously described [21] [22]. Luciferase assay (E1501, Promega) was performed in luciferase reporter hTERT-BJ1 cells treated with bedaquiline. Briefly, 1 × 10⁶ hTERT-BJ1 reporter cells were seeded in black-walled 96-well plates and then treated with 10 μM bedaquiline for 48 hours. Vehicle alone (DMSO) control cells were run in parallel. Three replicates were used for each condition. After 48 hours, luciferase assay was performed according to the manufacturer’s instructions. Light signal was acquired for 2 minutes in photons/second in the Xenogen VivoVision IVIS Lumina (Caliper Life Sciences), and the results were analyzed using the Living Image 3.2 sofware (Caliper Life Sciences). Luminescence was normalized using SRB (total proteins), as a measure of cell viability.

Statistical analysis. Data is represented as the mean ± standard error of the mean (SEM), taken over ≥ 3 independent experiments, with ≥ 3 technical replicates per experiment, unless otherwise stated. Statistical significance was measured using the analysis of variance (ANOVA) test or student t-test. P ≤ 0.05 was considered significant and all statistical tests were two-sided.

Validating the prognostic value of ATP5B. We used an open-access online survival analysis tool to interrogate publically available microarray data from up to 1,103 breast cancer patients [23]. Hazard-ratios were calculated, at the best auto-selected cut-off, and p-values were calculated using the logrank test and plotted in R. K-M curves were generated online using the K-M-plotter (as high-resolution TIFF files), using univariate analysis: http://kmplot.com/analysis/index.php?p=service&cancer = breast.

Funding

We thank the University of Manchester for providing start-up funds that contributed to the success of this study. The Sotgia and Lisanti Laboratories were supported, in part, by funding from the European Union (ERC Advanced Grant), Breast Cancer Now, the Healthy Life Foundation (HLF), and the Manchester Cancer Research Centre (MCRC). Ubaldo E. Martinez-Outschoorn was supported by the National Cancer Institute (NCI) of the National Institutes of Health (NIH), under Award Number K08-CA175193-01A1. Herbert B. Tanowitz was supported by the National Institutes of Health Award Number AI-1R21AI-124000.

Conflict of interest statement

The authors have no conflict of interests to declare.

REFERENCES


Supplementary Figure S1. K-M plots of OS (Overall Survival) are shown for ATP5B expression in different sub-groups of breast cancer patients (Panels A-E).