Metabolically induced intracellular pH changes activate mitophagy, autophagy, and cell protection in familial forms of Parkinson’s disease

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Introduction

Parkinson’s disease (PD) is a progressive, age-related currently incurable neurological disorder characterized by tremor, rigidity, bradykinesia, and postural instability. The histopathological hallmark of PD is the loss of dopaminergic neurons in substantia nigra of the midbrain and the formation of intraneuronal or intraglial inclusions of Lewy bodies consisting of aggregated α-synuclein. The majority of PD cases are sporadic with about 10% of the discovered in the last decades being familial forms of this disorder [1]. Despite the strong progress in understanding the etiology of PD, the molecular and cellular mechanisms of neurodegeneration remain unclear.

Mitochondrial dysfunction is strongly implicated in the mechanism of sporadic (toxic) and familial forms

Abbreviations
ATP, adenosine triphosphate; CCCP, carbonyl cyanide m-chlorophenyl hydrazone; FCCP, carbonyl cyanide-p-trifluoromethoxyphenylhydrazone; KO, knockout; PD, Parkinson’s disease; PINK1, PTEN-induced kinase 1; WT, wild-type.
of PD. Most proteins encoded by PD-related genes are connected to mitochondrial function. Altered adenosine triphosphate (ATP) production, overproduction of reactive oxygen species, and abnormal calcium handling in mitochondria are shown to be triggers for neuronal cell death in PD [2,3]. Additionally, damaged mitochondria might not be removed from neurons due to the alteration of the mechanism of mitochondrial quality control: the mitochondria-specific autophagic mechanism—mitophagy [4]. Parkinsonian genes are shown to be involved in the mechanism of mitophagy, specifically two of them—PINK1 and Parkin [5,6].

Autophagy is the process whereby intracellular components, including proteins and/or organelles, are delivered to lysosomes to be degraded. Autophagy maintains cellular homeostasis because it is the major contributor to basal turnover of cytosolic material, and a quality control system for proteins and organelles [7]. Processes of autophagy and mitophagy are also very important in PD due to the accumulation of α-synuclein toxic aggregates, which can target mitochondria and induce oxidative stress [8–10]. Considering this, activation of mitophagy and autophagy is suggested as a potential strategy for protection against misfolded aggregates and neurodegeneration in general [11]. There are a number of molecular pathways for mitophagy and autophagy and activation thereof can be beneficial and potentially neuroprotective for PD. Mitophagy and autophagy can be activated by different triggers including starvation and ischemic condition [12]. One of the major triggers for mitophagy used in experimental models is the application of high concentration of protonophores such as carbonyl cyanide-p-trifluoromethoxyphenylhydrazone (FCCP) or carbonyl cyanide m-chlorophenyl hydrazone (CCCP). We have suggested that these triggers may be involved in changes in intracellular pH and found that mitophagy and autophagy could also be activated by a short acidification of the cytosol [13]. However, the alternative inducer of pH decrease—nigericin—is toxic and cannot be used for neuronal protection.

Maintenance of intracellular pH is a sophisticated mechanism, which includes multiple enzymes and organelles, and importantly, cell metabolism [14,15]. Some metabolites, such as lactate, are believed to play an important role in brain energy metabolism and interaction between neurons and astrocytes [16,17]. Additionally, lactate concentration can dramatically increase during physical exercise [18] and it can induce angiogenesis and neurogenesis via lactate receptors [19]. Lactate is used by lactate dehydrogenase, which converts lactate to pyruvate. Both lactate and pyruvate can change intracellular pH and are metabolized inside cells. Considering this, here we tested the dose-dependent effects of lactate and pyruvate on intracellular pH of patient’s fibroblasts with various PD mutations. We also studied how these cytosolic pH changes influence mitophagy and cell viability.

Results

Basal intracellular pH is similar in control and in most Parkinson’s patients’ fibroblasts

To assess basal levels of cytosolic pH in control fibroblasts and patient’s fibroblasts with familial forms of PD, we used SNARF-1 as a fluorescent indicator. We found that in cells with A53T, SNCA, PINK1, PINK1/Parkin mutations, SNCA triplication [pH]i was in the range of 7.1–7.2 (Fig. 1A). However, in patient cells with Phosphoglycerate kinase type 1 mutation (c.1132A>C, p. Thy378Pro) intracellular basal pH was significantly lower compared with control cells (n = 40 cells; pH = 6.7 ± 0.1; P < 0.05; Fig. 1A).

Lactate dose-dependently reduce cytosolic pH in cells with familial forms of PD

Concentration of one of the major metabolites in the body, lactate, can dramatically change during physical activity and reach a concentration of up to 30 mm [20,21]. Application of sodium lactate (5–30 mM) to control fibroblasts dramatically reduced cytosolic pH in these cells (Fig. 1B,C). The minimal values were reached within 2–3 min with slow recovery of [pH]i, and 10 mM NH4Cl was then applied and washed out for calibration of the SNARF-1 signal (Fig. 1B). In control fibroblasts, the maximal decrease in pH was observed with a concentration of 10 mM lactate (N = 3; n = 30 cells; Fig. 1B,C). Effect of sodium lactate on the [pH]i of fibroblasts with PINK1 or PINK1/Parkin mutations was even bigger compared to control cells (N = 3; n = 30 cells; P < 0.05; Fig. 1D–F). Cells with α-synuclein pathology—SNCA triplication (Fig. 1G,H) or A53T mutation (Fig. 1I)—also had a significant reduction in pH in response to sodium lactate. Only one out of all studied cell lines—patient cells with phosphoglycerate kinase type 1 mutation (c.1132A>C, p. Thy378Pro)—had no or very moderate decrease of intracellular pH in response to 5–30 mM of sodium lactate (Fig. 1J,K). It should be noted that lowering of extracellular pH from 7.4 to 7.1 did not alter the effects of sodium lactate on intracellular pH of fibroblasts. Thus, application of sodium lactate can induce cytosolic acidification in control and fibroblasts from patients with familial forms of PD.
Pyruvate dose-dependently reduced cytosolic pH in cells with familial forms of PD

Application of sodium pyruvate (5–30 mM) to control fibroblasts induced a dose-dependent decrease of intracellular pH (Fig. 2A,B). Effect of sodium pyruvate on cells with familial forms of PD was mostly similar to the effects of lactate on pH of these cells. Thus, fibroblasts with Pink1 mutation showed a strong dose-dependence with the maximal decrease of [pH]i in response to 30 mM sodium pyruvate (Fig. 2C), while in cells with Pink1/Parkin mutation, addition of 10–30 mM pyruvate induced similar acidification of the cytosol of fibroblasts (Fig. 2D,E). Application of pyruvate to fibroblasts with SNCA triplication had a profound effect on cytosolic pH in all range of concentrations (5–30 mM) with maximal reduction at 30 mM pyruvate (Fig. 2H). In the same way as in experiments with lactate, patient cells with phosphoglycerate kinase type 1 mutation (c.1132A>C, p. Thy378Pro) had only very moderate decrease of intracellular pH in response to 5–30 mM of sodium pyruvate (Fig. 2I-J). It should be noted that lowering of extracellular pH from 7.4 to 7.1 did not change the effects of sodium pyruvate on intracellular pH of fibroblasts. Thus, millimolar concentration of pyruvate induced short-time acidification of the cytosol in control and fibroblasts with familial forms of PD.

Lactate increased mitophagy in control and PD patient’s fibroblasts

To assess the effect of various concentrations of lactate on mitophagy, we first pre-loaded the cells with MitoTracker Green and LysoTracker Red to stain mitochondria and lysosomes, respectively, treated cells with
Fig. 2. Effect of sodium pyruvate on [pH]i of PD patient’s fibroblasts. (A, D, F, I) representative SNARF-1 ratio traces in control, PINK1/Park2 mutation, SNCA triplication, and PGK type 1 mutation fibroblasts in response to sodium pyruvate. NH4Cl was added and washed out with HBSS for calibration of the SNARF-1 signal. Concentration-dependent changes of [pH]i in response to sodium pyruvate (millimolar concentrations labeled as P5-P30 on x-axis) in control (B), Pink1 mutations (C), Pink1/Park2 mutation (E), SNCA triplication (G), A53T mutation (H), and PGK type 1 mutation fibroblasts (J). Values are represented as mean ± SD. *P < 0.05. Independent experiments (n) are indicated as dots in the scatter plot.
lactate for 2 h and, after imaging, calculated the percentage of mitochondria colocalizing with lysosomal signal.

The basal level of mitophagy in control fibroblasts was relatively low—only 0.81% (N = 3 experiments; Fig. 3A,B). Incubation of the cells with lactate induced a significant increase in colocalization only at concentration of 30 mM (N = 3 experiments; P < 0.05; Fig. 3A,B).

Interestingly, despite Pink1 is implicated in the mechanism of mitophagy, fibroblasts with Pink1

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**Fig. 3.** Effect of sodium lactate on mitophagy in PD patient’s fibroblasts. Concentration-dependent effect of sodium lactate on co-localization of mitochondria [labeled by MitoTracker Green (green color) and lysosomes] (LysoTracker Red, red color on images) in control fibroblasts (A, B), fibroblasts with PINK1 mutation (C, D), PINK1/Park2 mutation (E, F), α-synuclein (SNCA) triplication (G, H), and A53T mutation (I, J). Scale bars in images 20 μm. Values are represented as mean ± SD. *P < 0.05. Independent experiments (n) are indicated as dots in the scatter plot.
mutation had a basal level of mitophagy comparable to control cells—1.08% (N = 3; Fig. 3C,D). 5–20 mM lactate even reduced the percentage of mitochondria colocalizing with lysosomes, but 30 mM lactate induced a significant 5-fold increase in the level of mitophagy in these cells (N = 3; to 5.46%; P < 0.05; Fig. 3C,D).

Fibroblasts with Pink1/Park2 mutation had a higher basal level of mitophagy—2.9% (N = 3; Fig. 3E,F). Lower concentrations of lactate—5–10 mM—reduced the percentage of mitochondria colocalizing with lysosomes (Fig. 3E,F) in the same way as in cells with Pink1 mutation. However, 20 mM and 30 mM of lactate significantly increased the level of mitophagy in fibroblasts with Pink1/Park2 mutations (Fig. 3E,F).

Interestingly, the different cells with distinct α-synuclein pathology had a different effect on the basal mitophagy level. Thus, fibroblasts with SNCA triplication had a lower level compared to control cells (0.30%, Fig. 3G,H), while in fibroblasts with the A53T mutation the percentage of colocalization was significantly higher—7.9% (N = 3; Fig. 3I-J). However, incubation of these cells with lactate increased the level of mitophagy in fibroblasts with both types of pathology—in SNCA triplication starting from 10 mM and higher (Fig. 3G,H) and in A53T—at concentrations 20 mM and 30 mM (Fig. 3I-J).

Thus, despite the difference in the basal levels of mitophagy, all studied fibroblasts had a significantly higher colocalization of mitochondria with lysosomes in response to higher concentrations of lactate (20–30 mM).

**Pyruvate increased mitophagy in control and PD patients’ fibroblasts**

5–10 mM pyruvate is often used as a substrate for complex I-related respiration for activation of oxidative phosphorylation in cells [22]. Incubation of control fibroblasts with 5–30 mM sodium pyruvate induced a significant increase in the percentage of mitochondria colocalizing with lysosomes, starting from a concentration of 10 mM (from basal 0.81% to 1.85% for 10 mM, N = 3 experiments; P < 0.05; Fig. 4A,B). Sodium pyruvate could also activate mitophagy in Pink1 mutation or Pink1/Park2 mutation fibroblasts but only at concentration 30 mM (Fig. 4C–F). Thus, in cells with Pink1 mutation 30 mM pyruvate induced a 5-fold increase in colocalization (N = 3 experiments; Fig. 4C,D) in Pink1/Park2-deficient fibroblasts the percentage of mitophagy grew from 3.1% to 9.3% (N = 3; P < 0.05; Fig. 4E,F).

Interestingly, the same tendency as in experiments with Pink1- and Pink1/Park2-deficient fibroblasts—reduction of the percentage of colocalized mitochondria with lysosomes with a small concentration of pyruvate and significant increase of mitophagy at 30 mM pyruvate—was observed in experiments with A53T mutation fibroblasts (Fig. 4G,H). It should be noted that the basal rate of mitophagy in these cells was much higher than in Pink1- or Pink1/Park2-deficient fibroblasts (7.9% compared to 1.08% and 3.14%, respectively; Fig. 4C,E,G).

In fibroblasts with α-synuclein triplication, incubation of cells with sodium pyruvate significantly increased the percentage of mitochondria colocalizing with lysosomes starting from 5 mM (Fig. 4I-J). Although pyruvate induced a 2- to 3-fold increase in mitophagy in these fibroblasts, the percentage of colocalization rose only to 1.32%, compared to basal 0.36%.

Thus, incubation of control PD patient fibroblasts with millimolar concentrations of sodium pyruvate increased the level of mitophagy in these cells.

**Lactate-induced autophagy in control and fibroblasts with familial forms of PD**

Autophagic flux was evaluated by assessing the lysosomal conversion of the autophagosome marker LC3 by immunoblotting [23]. Application of lactate (30 mM) induced an increase in the ratio LC3II/I, indicating a rise in the number of autophagosomes, that reached a peak after 30–60 min, followed by a decrease, which would indicate lysosomal degradation of the autophagosomes (Fig. 5A–C). To prove that the elevation in LC3II/I was due to an increase in the autophagic flux and not to a block, cells were treated with the V-ATPase inhibitor bafilomycin A1 (50 nM, 60 min), which inhibits lysosomal degradation. A further increase in LC3II/I ratio was observed in the presence of bafilomycin A1 (Fig. 5B,D), thus indicating that lactate activates the autophagic flux. Although no significant peak in LC3 levels was observed in PINK1 cells at the time-points studied, a significant increase in LC3II/I ratio clearly indicating activation of autophagy in PINK1-mutated fibroblasts by 30 mM lactate occurred after co-treatment with bafilomycin A1, suggesting the peak might have occurred at an earlier time-point. Thus, even a short application of 30 mM sodium lactate induces activation of autophagy in control fibroblasts and in fibroblasts with PD-related mutations.

**Lactate-induced mitophagy in brain slices from WT and PINK1 KO mice**

In order to identify whether acidification of the cytosol with lactate could induce mitophagy in brain cells, we...
used acute brain slices from adult wild-type (WT) and PINK1 knockout mice and a mitophagy detection kit. Interestingly, the basal level of mitophagy in PINK1 KO midbrain slices was 148.7% ± 5.6% of WT slices ($N = 5$; Fig. 6A,B). 90-min incubation of the acute midbrain slices with 10 mM sodium L-lactate increased

**Fig. 4.** Sodium pyruvate activated mitophagy in control and in fibroblasts with familial forms of PD. Concentration-dependent effect of sodium pyruvate on co-localization of mitochondria (labeled by MitoTracker Green (green color)) and lysosomes (Lysotracker Red, red color on images) in control fibroblasts (A, B), fibroblasts with PINK1 mutation (C, D), Pink1/Park2 mutation (E, F), α-synuclein (SNCA) triplication (G, H), and A53T mutation (I, J). Scale bars in images 20 μm. Values are represented as mean ± SD. *P < 0.05. Independent experiments (n) are indicated as dots in the scatter plot.
co-localization of mitochondria and lysosomes in cells of both WT and PINK1 KO brain slices \((N = 5; \text{Fig. 6A,B})\) inducing a 2-fold increase with higher lactate concentration—30 mM compared to basal levels \((N = 6; \text{Fig. 6A-B})\). Importantly, this effect in WT slices was even higher than the effect of 10 \(\mu M\) FCCP,
which is usually used for induction of mitophagy (Fig. 6B). Thus, incubation of the brain cells with sodium lactate can induce mitophagy in WT and PINK1 KO ex vivo.

**Lactate and pyruvate reduced the number of dead cells in control fibroblasts and cells with familial forms of PD**

Control fibroblasts and cells with PD mutations had ~6% dead cells in control conditions, with higher percentage in A53T mutation cell lines (9.8%, N = 7; Fig. 7A,B) and α-synuclein triplications (11.4%, N = 9; Fig. 7A,B). 24-h incubation of the cells with various concentrations of sodium lactate reduced the number of dead fibroblasts in the control cultures (to 3.3% ± 0.7% at 20 mM; N = 6; P < 0.05; Fig. 7A). However, for cells with PINK1 mutation incubation with lactate was protective only in higher concentrations, 20 mM and 30 mM (to 3.2% ± 0.2% and 2.2% ± 0.3% for 20 mM and 30 mM; accordingly, N = 6; P < 0.05; Fig. 7A), and only at concentration of 30 mM for PINK1/Park2 mutation or fibroblasts with A53T mutation (Fig. 7A). Incubation of the fibroblasts with α-synuclein triplications with lactate effectively reduced the number of dead cells in the full range of concentrations from 5 mM to 30 mM (Fig. 7A). Thus, incubation of the patient’s fibroblasts with millimolar concentrations of sodium lactate had no toxic effect on the cells and, in higher concentrations, was even protective.

24-h incubation of the fibroblasts with sodium pyruvate was protective for control cells, cells with A53T mutation, and α-synuclein triplications at concentrations from 5 mM to 30 mM (Fig. 7B). However, for cells with PINK1 mutation pyruvate protected cells from concentration 10 mM with maximal protection at 30 mM (to 2.1% dead cells; N = 7; P < 0.001; Fig. 7B). Surprisingly, 24-h incubation of fibroblasts with PINK1/Park2 mutation was protective only at lower concentrations (5–10 mM) but not at 20–30 mM (Fig. 7B). Thus, sodium pyruvate is protective for both control fibroblasts and for cells with PD mutations.

**Discussion**

Here, we have shown that two metabolites which participate in brain energy metabolism—pyruvate and lactate—can induce short-time concentration-dependent acidification of the cytosol. Importantly, these pH changes could be induced in cells with different genetic background. Effects of 30 mM lactate or pyruvate on intracellular pH of cells in the maximal value were comparable to effects of brain ischemia, where [pH]i falls to 6.5 or below [24]. Changes in [pH]i regulate multiple processes in the cells. Thus, in neurons short-term acidification of the cytosol could decrease their neuronal activity [25], and in fibroblasts, low pH is shown to inhibit the process of cell dividing [26]. Although low pH is shown to be a trigger for apoptosis [27], in our experiment profound acidification (which was restored in our experiments within minutes) had only positive cell protective effect on control fibroblasts and cells with genetic form of PD (Fig. 7). However, considering the mitochondrial dysfunction in cells with these mutations [8,28,29] we cannot exclude effects of pyruvate and lactate on bioenergetics [30]. Additionally, in fibroblasts lactate can induce switch from oxidative phosphorylation to glycolysis that also potentially can have an effect of quality control of fibroblasts [31].

PD-related mutations induce neurodegeneration in specific brain areas, while neurons and astrocytes from different brain areas vary in their rate of energy metabolism and redox balance that may have an effect on mitophagy [32,33]. However, PD patients’ fibroblasts are shown to be relevant models to study the effects of PD mutations on mitochondrial metabolism with results comparable to neuronal [29], and despite some limitations, using fibroblasts we can assess the effect of lactate and pyruvate on mitophagy and autophagy on cells with PD mutations.

Previously, we have shown that acidification of the cytosol with FCCP and nigericin induced mitophagy and PINK1-dependent and independent mitophagy and autophagy [13]. It should be noticed that changes in [pH]i in response to millimolar concentration of sodium lactate and sodium pyruvate were comparable with the effects of 10 μM FCCP and 1–3 μM nigericin, which induced mitophagy and autophagy. However, decrease in [pH]i in response to lactate and pyruvate did not induced cell death, which was observed with these ionophores.

PINK1- and Parkin-dependent mitophagy requires loss of mitochondrial membrane potential [34]. Lactate and pyruvate are mostly used to recover mitochondrial membrane potential [22,35], and considering this, the effect of lactate and pyruvate on mitophagy and autophagy is independent from mitochondrial membrane potential and induced by intracellular acidification. Importantly, decrease of [pH]i by lactate and pyruvate successfully induced mitophagy and autophagy in cells that lack PINK1 or PINK1/Parkin function that additionally confirms PINK1/Parkin-independent pathway of mitophagy, induced by millimolar concentrations of these compounds.
However, we cannot exclude this pathways’ activation in cells with other mutations.

Levels of lactate in blood and intracellular acidification can be induced by a number of factors, which are shown to be beneficial, calorie restriction [36], and, importantly, physical exercise [37,38]. We can suggest that an elevation of the lactate level in the time of physical exercises of patients with PD could be potentially beneficial for activation of mitophagy and autophagy and consequently aiding neuroprotection.

Materials and Methods

Cell cultures

Fibroblasts were generated from a 4-mm skin punch biopsy taken under local anesthetic following local ethical approval. All patients gave full informed consent. We have ethical approval for investigating patients with informed consent and taking skin samples for research approved by University College London Hospital ethics committee (Number: 07/N018). Biopsies were dissected into ~1-mm pieces and cultured in DMEM, 10% FBS, and 1% Gluta-MAX until fibroblasts were seen to grow out from the explants. When fibroblasts reached confluence, they were detached from culture dishes using TrypLE Express (Invitrogen) and transferred to larger culture vessels for further expansion and cryopreservation. Age, sex, clinical diagnosis, and gene mutations of the donors are depicted in Table 1.

Pyruvate and lactate applications

Sodium pyruvate and sodium lactate were dissolved in buffered HBSS at neutral pH (pH 7.4), and the applications of these compounds in all experiments were controlled for extracellular pH changes (all neutral).

Measurements of pH_{cvt}

Cells were loaded for 30 min at room temperature with 5 μM 5-(and-6)-carboxyl SNARF-1 AM and 0.005% pluronic acid in a Hank’s Balanced Salt Solution (HBSS) composed of (mM): 156 NaCl, 3 KCl, 1 MgSO_4, 1.25 KH_2PO_4, 2 CaCl_2, 10 glucose, and 10 HEPES; pH adjusted to 7.4 with NaOH. NH_4Cl was added and washed out to calibrate SNARF ratio. Confocal images were obtained using a Zeiss 710 confocal microscope equipped with 40× oil immersion objective. SNARF fluorescence was excited at 514 nm with argon laser light. Fluorescence was collected at 550–600 and 650–700 nm for ratiometric [pH] measurement every 10 s. SNARF-1 signal was calibrated according to the manufacturer’s instructions.

Acute brain slices

Animals – PINK1-deficient mice, originally generated by Lexicon Genetics Inc. (The Woodlands, TX, USA), were obtained under MTA through Julian Downward, CRUK, London. Mice were maintained on a 12-h light/12-h dark cycle with free access to water and food. Animal husbandry and experimental procedures were performed in full

Fig. 7. Millimolar concentrations of sodium lactate and sodium pyruvate protect control and fibroblasts with familial PD against cell death. (A) Percentage of dead cells (labeled with PI) in control, and fibroblasts PINK1 mutation, PINK1/PARK2 mutations, A53T mutation and SNCA triplication after 24 h treatment with 5-, 10-, 20- or 30-mM sodium L-lactate. N = 7; (B) Percentage of dead cells in cultures of human fibroblasts treated with 5-, 10-, 20-, or 30-mM sodium pyruvate for 24 h. N = 7. Values are represented as mean ± SD. *P < 0.05; **P < 0.01; ***P < 0.001.
Table 1. Donors’ information.

| Line       | Mutation                                                                 | Diagnosis          | Age | Sex   |
|------------|---------------------------------------------------------------------------|--------------------|-----|-------|
| Control 1  | Healthy donor                                                            | Healthy donor      | 56  | Female|
| Control 2  | Healthy donor                                                            | Healthy donor      | 49  | Female|
| Control 3  | Healthy donor                                                            | Healthy donor      | 53  | Male  |
| A53T       | A53T het in SNCA                                                          | Severe PD          | 51  | Female|
| PINK1      | homozygous p. Try90LeufsX12 in PINK1                                     | PD                 | 52  | Female|
| PINK1/Park2| Park2/Pink1 double heterozygous PARK2 R725W/WT + PINK1p. Try90Leuf*12/WT  | PD                 | 75  | Male  |
| SNCA trip  | Triplication in SNCA                                                     | Early-onset PD     | 55  | Female|
| PGK-1      | Phosphoglycerate kinase type 1 mutation (c.1132A>G)                       |                    |     |       |
| A53T       | A53T het in SNCA                                                          |                    |     |       |
| PINK1      | PINK1 p. Thy378Pro                                                        |                    |     |       |
| Control 1  | Healthy donor                                                            |                    |     |       |
| Control 2  | Healthy donor                                                            |                    |     |       |
| Control 3  | Healthy donor                                                            |                    |     |       |

compliance with the United Kingdom Animal (Scientific Procedures) Act of 1986 and with approval of the University College London Animal Ethics Committee. Animals were genotyped by PCR amplification of ear biopsy material in the following manner: genomic DNA was isolated from biopsy tissue using the Extract-N-Amp Tissue PCR kit (Merck, Burlington, MA, USA) and amplified with primers PINK1-26 (5'-CTGCCCTCAGGTCCTCTAATGC-3'), PINK1-27 (5'-GGAGAGGAGCCATGGAAATGT-3'), and Neo (5'-GCAGGGCATCGCCTTCTATC-3').

Western blots

Protein extracts were collected in ice-cold RIPA lysis buffer supplemented with protease and phosphatase inhibitors (Thermo Fisher, Paisley, UK). Samples were snap-frozen, sonicated, and centrifuged at 22 000 g, and protein content of the extracts was determined by the Pierce™ BCA protein assay (Thermo Fisher, Paisley, UK).

15–20 µg of protein was then fractionated on a SDS polyacrylamide gel (4%–12%) (Thermo Fisher, Paisley, UK), transferred to an Immobilon-P PVDF membrane (Merck), and blocked with 5% non-fat milk. Membranes were incubated overnight with the corresponding primary antibodies diluted in 5% bovine albumin serum: LC3 1:1000, p62 1:1000 or beta-actin (4970) 1:5000, all antibodies diluted in 5% bovine albumin serum: LC3 1:1000, p62 1:1000 or beta-actin (4970) 1:5000, all from Cell Signaling Technologies (Danvers, MA, USA) and afterward with the corresponding specie-specific HRP-conjugated secondary antibodies. The luminol-based Pierce™ ECL Western Blotting Substrate (Thermo Fisher Scientific) was used to detect the HRP activity. Protein band densities were quantified using IMAGEJ (NIH, Bethesda, MD, USA) after scanning the X-ray films. In order to compare the results between experiments, in all cases results were normalized to t = 0.

Mitochondria and lysosomes colocalization

For the identification of mitochondrial and lysosomal colocalization, cells were loaded with 200 nm Mitotracker Green FM and 50 nm LysoTracker Red DND-99 in HBSS for 30 min before experiments (including the treatment of cells with lactate and pyruvate).

The 488-nm Argon laser line was used to excite Mitotracker Green FM fluorescence, which was measured between 505 and 530 nm. Illumination intensity was kept to a minimum (about 1% of laser output) to avoid phototoxicity and the pinhole set to give an optical slice of ~2 µm. For LysoTracker Red DND-99, the 543 nm Ne/He laser line was used with measurement above 650 nm. All data presented were obtained from at least 5 coverslips and 2–3 different cell preparations.

Mitophagy detection kit

Mitophagy Detection Kit (Dojindo Molecular Technologies Inc., Kumamoto, Japan) is composed of a reagent for the detection of mitophagy (Mitophagy dye), and a reagent for labeling of the lysosomes (Lyso dye) was used to assess the levels of mitophagy. When mitophagy is induced upon certain treatment, the Mitophagy dye from damaged mitochondria increases in fluorescence and damaged mitochondria fuse to the lysosomes.

In brief, acute slices from WT and PINK1 KO mice were incubated with the Mitophagy dye (100 nmol·L⁻¹) and consequently treated with different concentrations of Lactate (10 mM, 30 mM) or FCCP (10 µM). After incubation period of 30 min, Mitophagy dye was washed and slices were incubated with the Lyso dye (1 µmol·L⁻¹) for 30 min. Slices were then washed and imaged with Zeiss 710 inverted confocal microscope (Mitophagy Dye, Ex: 561 nm; Lyso dye, Ex:488/Em:550 nm), correspondingly.

Cell death

Sodium lactate or sodium pyruvate in concentrations 5, 10, 20, or 30 mM or the same volume of buffer as a control were applied to the extracellular medium of the fibroblasts.
and incubated for 24 h. Cells were then loaded for 15 min with 20 μM propidium iodide and 10 μM Hoechst 33342. While Hoechst is a blue, fluorescent dye that stains chromatin DNA, propidium iodide is only permeable to dead cells and shows red fluorescence, so it is possible to calculate the percentage of dead cells (showing red fluorescence) versus total number of cells (showing blue fluorescence). Fluorescence measurements were obtained on an epifluorescence-inverted microscope equipped with a 20× fluorite objective. Excitation light [for Hoechst 33342 380 nm and for PI (530 nm)] provided by a Xenon arc lamp. Emitted fluorescence light was reflected through a 515-nm long-pass filter to a cooled CCD camera (Retiga, QImaging, Canada). A total number of 800–1000 cells were counted in 4–5 different fields per coverslip. Experiments were repeated 4–7 times with separate independent cultures.

**Statistical analysis**

Results are expressed as means ± SEM (standard error of the mean); one-way ANOVA with post-hoc Tukey’s HSD correction for multiple comparisons and Student’s t-test was used, where appropriate. Statistical analysis was performed using Origin 2019 (Microcal Software Inc., Northampton, MA, USA) software. Differences were considered to be significantly different if P < 0.05.

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**Conflict of interest**

The authors declare no conflict of interest.

**Author contributions**

AYA, AVB, AVG, NE, and PA involved in conceptualization. NK, PA, NE, OS, and AVB investigated and analyzed the data. AYA, HH, AVG, and UZM performed resources. AYA, NK, NE, and PA wrote original draft. AYA, NK, NE, PA, and AVB reviewed and edited the data. UZM, HH, OS, AVB, and AYA contributed to funding acquisition.

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