NICOTINAMIDE DEFICIENCY IN PRIMARY OPEN-ANGLE GLAUCOMA

Judith Kouassi Nzoughet[1], Juan Manuel Chao de la Barca[1,2], Khadidja Guehlouz[3], Stéphanie Leruez[3], Laurent Coulbault[4], Stéphane Allouche[4], Cinzia Bocca[1], Jeanne Muller[3], Patrizia Amati-Bonneau[1,2], Philippe Gohier[3], Dominique Bonneau[1,2], Gilles Simard[2], Dan Milea[5], Guy Lenaers[1], Vincent Procaccio[1,2], Pascal Reynier[1,2]

[1]Equipe Mitolab, Unité Mixte de Recherche MITOVASC, CNRS 6015, INSERM U1083, Université d'Angers, Angers, France

[2]Département de Biochimie et Génétique, Centre Hospitalier Universitaire, Angers, France

[3]Département d'Ophtalmologie, Centre Hospitalier Universitaire, Angers, France

[4]Service de Biochimie, EA4650, Centre Hospitalier Universitaire, Caen, France

[5]Singapore Eye Research Institute, Singapore National Eye Centre, Duke-NUS, Singapore

Corresponding author : Judith Kouassi Nzoughet, PhD, Equipe Mitolab, Institut MITOVASC, UMR CNRS 6015, INSERM U1083, 4 rue Larrey, 49933 Angers cedex 9, Angers, France; Tel: +33 (0) 244688412; Email: judith.kouassinzoughet@univ-angers.fr

Short title: Nicotinamide deficiency in glaucoma

ABSTRACT

PURPOSE: To investigate the plasma concentration of nicotinamide in primary open-angle glaucoma (POAG).

DESIGN: Case-control study

METHODS: Plasma of 34 POAG individuals were compared to that of 30 age- and sex-matched controls using a semi-quantitative method based on liquid chromatography coupled to high-resolution mass spectrometry. Subsequently, an independent quantitative method, based on liquid chromatography coupled to mass spectrometry, was used to assess nicotinamide concentration in the plasma from the same initial cohort and from a replicative cohort of 20 POAG individuals and 15 controls.

RESULTS: Using the semi-quantitative method, the plasma nicotinamide concentration was significantly lower in the initial cohort of POAG individuals compared to controls (-36 %, False Discovery Rate corrected *p*-value = 0.0027) and further confirmed in the same cohort, using the targeted quantitative method, with mean concentrations of 0.14 µM (median: 0.12 µM; range: 0.06-0.28 µM) in the POAG group (-30 %; $p = 0.022$), and 0.19 µM (median: 0.18 µM; range: 0.08-0.47 µM) in the control group. The quantitative dosage also disclosed a significantly lower plasma nicotinamide concentration (-33 %; $p = 0.011$) in the replicative cohort with mean concentrations of 0.14 µM (median: 0.14 µM; range: 0.09-0.25 µM) in the POAG group, and 0.19 µM (median: 0.21 µM; range: 0.09-0.26 µM) in the control group.

CONCLUSIONS: Glaucoma is associated with lower plasmatic nicotinamide levels, compared to controls, suggesting that nicotinamide supplementation might become a future therapeutic strategy. Further studies are needed, in larger cohorts, to confirm these preliminary findings.

INTRODUCTION

Glaucoma, the leading cause of irreversible blindness worldwide, is due to a progressive optic neuropathy involving the loss of retinal ganglion cells (RGCs) [1]. Although age and increased intraocular pressure (IOP) are the main risk factors of the disease, other factors may contribute to the occurrence and progression of glaucoma, such as genetic variants, which account for approximately 5 % of the cases, together with vascular impairment, and metabolic disturbances [2].

Since the local absence of myelinated axons in the intraocular portion of the optic nerve leads to high energy requirements, the question of mitochondrial dysfunction has been raised in glaucoma similarly to what is observed in hereditary optic neuropathies [3]. Indeed, several studies have revealed a true respiratory chain deficiency in glaucoma [4,5]. The central role of mitochondrial dysfunction was recently demonstrated in a DBA/2J mouse model of glaucoma with high IOP [6,7]. These authors highlighted decreased retinal levels of nicotinamide adenine dinucleotide (NAD), an essential oxidation-reduction cofactor, and showed that the oral administration of high doses of nicotinamide, a precursor of NAD, structurally and functionally prevented the loss of RGCs, posing the rationale for a translational application in humans [8].

Nicotinamide, also known as vitamin B3 or PP (pellagra-preventive) vitamin, is a water-soluble vitamin, the deficiency of which causes pellagra, a systemic condition associating diarrhoea, dermatitis and dementia, and ultimately leading to death. Despite its potential role in the pathogenesis of glaucoma, no study to our knowledge has yet established the involvement of nicotinamide in individuals with primary open-angle glaucoma (POAG)[9].

To gain insight into the pathophysiology of POAG, we applied a non-targeted metabolomics approach, based on liquid chromatography coupled to high resolution mass spectrometry (LC-HRMS) [10], to compare the plasma of individuals with POAG and controls. This study, showing that nicotinamide was the most discriminating metabolite of the signature, led us to investigate the plasma concentration of nicotinamide in individuals with POAG, as reported here.

METHODS

Study participants

Participants were included in the study after having given their informed written consent for the research, which was conducted according to the ethical standards of the Helsinki Declaration (1983), and with the approval of our Ethical Committee (Comité de Protection des Personnes (CPP) OUEST 2), agreement number: CB 2013-04.

Individuals were recruited from the Department of Ophthalmology of Angers University Hospital, France. The initial diagnosis of POAG was based on consensual criteria, i.e. glaucomatous optic nerve damage with progressive optic disc cupping, associated with an IOP >21 mmHg [11]. All the patients with POAG had an elevated IOP at the time of initial diagnosis, as well as open irido-corneal angles, as determined by gonioscopic

examination. Individuals with isolated ocular hypertension, normal tension glaucoma, or any secondary form of glaucoma, were excluded from the study. Standard automated perimetry (Humphrey field analyser, Carl Zeiss, Dublin, CA, USA) with the 24-2 SITA-Fast algorithm was performed on all individuals with POAG, and values of the visual field mean defect (VF-MD) were used to grade the severity of POAG as “mild” with values lower than -6 dB, “moderate” with values between -6 dB and -12 dB, and “severe” with values higher than -12 dB (perimetric Hoddap-Parrish-Anderson criteria). The reliability indices retained were false positive or false negative rates under 15 %, and fixation losses under 20 %. The other tests performed on patients with POAG included evaluation of the thickness of the retinal nerve fibre layer (RNFL), using spectral domain optical coherence tomography (OCT), and measurement of the central corneal thickness (CCT) (Cirrus OCT, Carl Zeiss Meditec, Dublin, CA, USA). The best-corrected visual acuity was measured using the Monoyer decimal charts, with the results converted into logMAR units for statistical analysis. The IOP was measured using the Goldmann applanation tonometer. The history of glaucoma treatment was documented.

Control subjects were selected among healthy individuals undergoing cataract surgery at the same Department of Ophthalmology. Their inclusion criteria were: visual acuity ≥ 20/50 and the absence of any other associated ocular condition, excepting cataract. The exclusion criteria were: a family history of glaucoma, ocular hypertension or any other intraocular pathology, including retinal disorders.

Our study was carried out on two distinct cohorts recruited from the Department of Ophthalmology of Angers University Hospital. The first cohort, referred as the “initial cohort”, was composed of 34 individuals with POAG and 30 controls, and the second cohort, referred as the “replicative cohort”, was composed of 20 individuals with POAG and 15 controls. The initial cohort was subjected to a non-targeted metabolomics study, which led to the discovery of nicotinamide deficiency. This was followed by a quantitative analysis as developed in the Department of Biochemistry of Caen University Hospital, France. The replicative cohort was used only for the specific quantitative analysis of nicotinamide.

Blood samples from each participant were collected in heparin tubes at least three hours after the last meal, transported on ice, and processed through the Biological Resource Centre of the Hospital of Angers. Blood samples were centrifuged immediately for 10 minutes at 3000 g at +4 °C to recover the supernatant (plasma), which was stored at -80 °C in 500 µL aliquots, until analysis. The delay between sampling and plasma storage was less than an hour.

Non-targeted semi-quantitative LC-HRMS nicotinamide analysis of plasma samples from the initial cohort

The non-targeted LC-HRMS analysis was performed according to a method designed for the semi-quantitative measurement of 501 metabolites [10]. Briefly, metabolites were extracted from plasma samples using ice-cold methanol. The extracts were analysed by reverse phase (RP) ultra-high-performance liquid chromatography (UHPLC, Dionex™ UltiMate 3000 coupled to a high-resolution mass spectrometer (HRMS) Thermo Scientific™ Q Exactive™ platform). Acquisitions were performed in heated electrospray positive ionization (HESI+) modes. The semi-quantitative measurement of nicotinamide was based on an in-house library composed of 501 endogenous metabolites, created using the Mass Spectrometry Metabolite Library of Standards (IROA Technology, Bolton, MA, USA). The method was validated over three days, and the extraction efficiency as well as the accuracy, precision, repeatability, and linearity of the method were assessed to ensure the quality of the results [10].

The parameters of Nicotinamide in the non-targeted method were the following: ionization: positive mode; RT: 1.66 min; Formula: C6H6N2O; M+H: 123.0553; Fragment ions: 80.0501 and 96.0449. The repeatability (CV%) of the method for nicotinamide was as follow: 5.5% for peak area, 7.6% for peak intensity, 0.7% for retention time (RT) and 0% for m/z ratio. Mass spectrometry and chromatography accuracies were also satisfactory, with respectively 1 Δppm and 0.05 ΔRT through the sequence; R^2 for dilutions linearity (1, 1/2, 1/4 dilutions) was equal to 0.9.

Quantitative LC-MS/MS nicotinamide analysis of plasma samples from the initial and replicative cohorts

A blind independent external validation of nicotinamide dosage was performed on plasma samples from both the initial and replicative cohorts using a targeted LC-MS/MS method specifically designed for the quantification of nicotinamide. Nicotinamide (NM) and its isotope-labelled analogue, nicotinamide-d_4 (NM-d_4), were purchased from LGC Standards GmbH (Wesel, Germany). Fifty microliters of plasma were mixed with 20 µL Internal Standard (IS) solution (NM-d_4), and 130 µL of a cold methanol/acetonitrile solution (50/50; V/V) to precipitate proteins. Samples were incubated on ice for 5 min, and then centrifuged at 10 000 g for 5 min. Fifty µL of supernatant were mixed with 550 µL of water and filtered (0.45 µm) before injection into the chromatography and mass spectrometry system.

Liquid chromatography was conducted on a UFLC Prominence chromatographic system (Shimadzu, Kyoto, Japan) connected to a SCIEX QTRAP® 5500 mass spectrometer, equipped with a turbo V ion spray source (SCIEX, Toronto, Canada). Six µL of supernatant were injected, and chromatographic separation was performed at +40 °C using a Pursuit pentafluorophenyl (PFP) column (150 x 2.1 mm, 3.5 µm; Agilent technologies, Santa Clara, CA, USA) connected to a guard column (Pursuit PFP). The flow rate was 0.4 $ml.min^{-1}$. A gradient mobile phase was performed and started with 98 % mobile phase A (0.1% formic acid in water) and 2 % mobile phase B (methanol). After 1.5 min post-injection, the percentage of mobile phase B increased linearly from 2 % to 80 % in 1 min, and stayed at 80 % mobile phase B during 0.5 min. The return to baseline conditions (2 % B) was operated after 4 min and the system was allowed to

stabilize for 2.3 min before the next injection. The total chromatographic run time was 6.3 min.

Mass spectrometry analysis was conducted using the electrospray ion (ESI) source in the positive mode. The parameters of the ion source were as follows: temperature 450 °C, ESI voltage 5500 V, Gas GS1 70 psi, Gas GS2 60 psi, CAD gas 8 psi, and Curtain gas 40 psi. For nicotinamide quantification, Multiple Reaction Monitoring (MRM) transitions were respectively m/z 123→80 and m/z 127→84 for nicotinamide and nicotinamide-d_4 respectively. For nicotinamide transition, the instrument parameters were 91 V, 27 V, and 12 V for DP, CE, and CXP, respectively. For nicotinamide-d_4 transition, the instrument parameters were 81 V, 27 V, and 38 V for DP, CE, and CXP, respectively.

Five standard calibration points were made in water at final concentrations of 0.082, 0.205, 0.410, 0.819, and 1.639 µM for nicotinamide. A solution of nicotinamide-d_4 was prepared by dilution in water at a final concentration of 3.966 µM (IS solution).

Evaluation of the sensitivity and specificity of the protocol showed that the targeted LC-MS/MS method gave good results. The calibration curve was linear up to 200 µg/L (r>0.999), the limit of quantification was 5 µg/L, and the recovery rate was 101±3 % in plasma samples spiked with nicotinamide. During the reproducibility assay, the coefficients of variation (CV) were lower than 5 % at three levels of concentration (CV = 4.8%, 20.4±1.0 µg/L for the low-level control). The retention times were 1.73 min and 1.71 min for nicotinamide and nicotinamide-d_4, respectively. Typical chromatograms for nicotinamide and nicotinamide-d_4 in plasma samples are shown in the supplemental Figure.

Statistical analyses

The data matrix from non-targeted metabolomics contained one hundred and sixty metabolites; univariate analysis was performed using the non-parametric Wilcoxon rank sum test with Benjamini-Hochberg correction and keeping the False Discovery Rate (FDR) below 5%. These analyses were conducted using Metaboanalyst v4.0 [12].

Univariate analyses of clinical data were carried out using two-tailed Student's *t*-test, with differences being considered significant at $p < 0.05$. A median test was used to compare the median concentrations of nicotinamide found in individuals with POAG *versus* controls, in both the initial and replicative cohorts. The level of significance for the two-tailed test was set at $\alpha = 0.05$. This analysis was performed using SPSS Statistics v22 (IBM, Bois-Colombes, France).

RESULTS

Clinical characteristics of individuals with POAG and controls

Comparisons between individuals with POAG (n=34) and controls (n=30) from the initial cohort, in terms of demographic and comorbidity data, medical conditions and general ophthalmological features, are presented in Table 1. There were no significant differences between the two groups in terms of mean age, sex ratio, systemic medications, or mean IOP.

Comparisons between individuals with POAG (n=20) and controls (n=15) from the replicative cohort, in terms of demographic and comorbidity data, medical conditions and general ophthalmological features are presented in Table 2. There were no significant differences between the two groups in terms of mean age, sex ratio, or systemic medications, except for anti-hypertensives ($p<0.02$) and lipid-lowering medications ($p<0.04$), which were significantly lower in individuals with POAG than in controls. In contrast to the initial cohort, the replicative cohort showed a difference between the two groups regarding the IOP, which was significantly higher in individuals with POAG compared to controls ($p<0.001$), the discrepancy with the initial cohort being due to the presence in the replicative cohort of patients with an insufficiently efficacious treatment for IOP.

Plasma nicotinamide concentrations

The univariate analysis of the results obtained using the semi-quantitative LC-HRMS method on plasma samples from the initial cohort revealed significant differences between individuals with POAG and controls, with nicotinamide being the most discriminant metabolite (False Discovery Rate corrected $p = 0.0027$), showing an average nicotinamide decrease of 36 % in individuals with POAG compared to controls (Figure).

This observation, subsequently tested in both the initial and replicative cohorts, using an independent quantitative measurement of nicotinamide designed for a clinical laboratory setting, supported the results obtained with the metabolomics analysis (Figure). The median concentrations of nicotinamide found in individuals with POAG and controls were 0.12 µM (0.06-0.28 µM) *vs*. 0.18 µM (0.08-0.47 µM), and 0.14 µM (0.09-0.25 µM) *vs*. 0.21 µM (0.09-0.26 µM), respectively, in the initial and replicative cohorts, corresponding to a reduction of 30 % ($p = 0.022$) and of 33 % ($p = 0.011$) of the nicotinamide concentration in the initial and replicative POAG *vs.* control cohorts, respectively. The mean concentrations of nicotinamide found in individuals with POAG and controls were 0.14 µM *vs*. 0.19 µM, and 0.14 µM *vs*. 0.19 µM, respectively, in the initial and replicative cohorts.

DISCUSSION

Mitochondrial dysfunctions and decreased NAD content are hallmarks of aging in most organs [13,14] and many experimental studies, essentially performed on mouse models, have revealed that strategies based on NAD repletion effectively reverse age-related phenotypes and disorders [15,16], such as those affecting the skeletal muscles [17], the brain [18], and the endothelium [19]. Recent studies on the DBA/2J mouse model of glaucoma, have further confirmed a dose-dependent protective effect of NAD repletion on the optic nerve, reaching a protection level of 93% at the highest nicotinamide dose tested (2000 mg/kg/day), despite a continuously elevated IOP [6,7,20]. More importantly, the age-dependent vulnerability of the RGCs in these mice is correlated with the decreased concentration of NAD in the retina. Thus, the nicotinamide deficiency we observed in the blood of individuals with POAG parallels the NAD depletion observed in the DBA/2J mouse model. Interestingly, our study of plasma samples from individuals affected by dominant optic atrophy due to OPA1 mutations, another form of an age-dependent progressive optic neuropathy due to mitochondrial impairment, also revealed a 50 % reduction of nicotinamide whose chemical formula is $C_6H_6N_2O$ [21].

The main function of NAD as a redox cofactor consists of providing electrons from oxidized nutrients to the mitochondrial respiratory chain complex I, thus sustaining ATP production. In parallel, NAD-consuming enzymes, such as those involved in DNA repair, e.g. poly (ADP-ribose) polymerase (PARP), may consume NAD stocks excessively during aging, in particular to prevent the accumulation of DNA mutations [13]. This excessive NAD consumption may compromise NAD-dependent complex I activity, the deficiency of which is frequently associated with inherited optic neuropathies, because of the particularly high energy required by RGCs to transduce visual information from the retina to the brain. In this respect, the lymphoblasts of patients with POAG showed a mitochondrial complex I deficiency reflecting a systemic mitochondrial impairment [4,5]. In addition, using targeted metabolomics on the plasma of POAG patients compared to controls, we have recently shown a metabolic profile combining the impaired utilization of energetic substrates and decreased levels of polyamines, attesting to mitochondrial dysfunction, and premature ageing [22]. Since nicotinamide is one of the main contributors to the regeneration of NAD through a salvage metabolic pathway, nicotinamide deficiency could reflect excessive age-related NAD consumption, which subsequently leads to complex I deficiency, and the energetic failure responsible for the degeneration of RGCs.

The main limitation of this study consists in the relatively small number of individuals in both the initial and replicative cohorts. However, we found a significant decrease in vitamin B3 levels in patients with POAG compared to controls using two different techniques, with highly similar results in the two independent cohorts. Further studies with larger cohorts are also required, as well as investigations in populations with various cultural dietary habits, to find out whether this deficiency is consistently associated with POAG and eventually with other forms of glaucoma. Finally, the convergence between recent studies showing that oral administration of nicotinamide prevents glaucoma in the DBA/2J mouse model [6,7,20] and our study on patients with

POAG, opens promising therapeutic perspectives based on nicotinamide supplementation.

ACKNOWLEDGMENTS/DISCLOSURE

a. Funding/Support

We acknowledge support from the *Institut National de la Santé et de la Recherche Médicale* (*INSERM)*, the *Centre National de la Recherche Scientifique* (*CNRS)*, the *University of Angers*, the *University Hospital of Angers*. We also thank the following patients' foundations for their support: "*Fondation VISIO*", "*Ouvrir les Yeux*", "*Union Nationale des Aveugles et Déficients Visuels*" "*Association contre les Maladies Mitochondriales*", "*Retina France*", "*Kjer France*", "*Fondation Berthe Fouassier*", *"Fondation pour la Recherche Médicale"* and *"Association Point de Mire"*.

b. Financial Disclosures

No financial disclosures.

c. Other acknowledgments

We are grateful to Kanaya Malkani for critical reading and comments on the manuscript and to Dr. Odile Blanchet and the team of the *Centre de Ressources Biologiques* of the University Hospital of Angers for processing the biobank samplings.

REFERENCES

1. Jonas JB, Aung T, Bourne RR, Bron AM, Ritch R, Panda-Jonas S. Glaucoma. *Lancet Lond Engl*. 2017;390(10108):2183-2193. doi:10.1016/S0140-6736(17)31469-1

2. Burgess LG, Uppal K, Walker DI, et al. Metabolome-Wide Association Study of Primary Open Angle Glaucoma. *Invest Ophthalmol Vis Sci*. 2015;56(8):5020-5028. doi:10.1167/iovs.15-16702

3. Osborne NN, Núñez-Álvarez C, Joglar B, Del Olmo-Aguado S. Glaucoma: Focus on mitochondria in relation to pathogenesis and neuroprotection. *Eur J Pharmacol*. 2016;787:127-133. doi:10.1016/j.ejphar.2016.04.032

4. Lee S, Sheck L, Crowston JG, et al. Impaired complex-I-linked respiration and ATP synthesis in primary open-angle glaucoma patient lymphoblasts. *Invest Ophthalmol Vis Sci*. 2012;53(4):2431-2437. doi:10.1167/iovs.12-9596

5. Van Bergen NJ, Crowston JG, Craig JE, et al. Measurement of Systemic Mitochondrial Function in Advanced Primary Open-Angle Glaucoma and Leber Hereditary Optic Neuropathy. *PloS One*. 2015;10(10):e0140919. doi:10.1371/journal.pone.0140919

6. Williams PA, Harder JM, Foxworth NE, et al. Vitamin B3 modulates mitochondrial vulnerability and prevents glaucoma in aged mice. *Science*. 2017;355(6326):756-760. doi:10.1126/science.aal0092

7. Williams PA, Harder JM, John SWM. Glaucoma as a Metabolic Optic Neuropathy: Making the Case for Nicotinamide Treatment in Glaucoma. *J Glaucoma*. 2017;26(12):1161-1168. doi:10.1097/IJG.0000000000000767

8. Liebmann JM, Cioffi GA. Nicking Glaucoma with Nicotinamide? Phimister EG, ed. *N Engl J Med*. 2017;376(21):2079-2081. doi:10.1056/NEJMcibr1702486

9. Ramdas W, Schouten J, Webers C. The Effect of Vitamins on Glaucoma: A Systematic Review and Meta-Analysis. *Nutrients*. 2018;10(3):359. doi:10.3390/nu10030359

10. Kouassi Nzoughet J, Bocca C, Simard G, et al. A Nontargeted UHPLC-HRMS Metabolomics Pipeline for Metabolite Identification: Application to Cardiac Remote Ischemic Preconditioning. *Anal Chem*. 2017;89(3):2138-2146. doi:10.1021/acs.analchem.6b04912

11. Weinreb RN, Khaw PT. Primary open-angle glaucoma. *Lancet Lond Engl*. 2004;363(9422):1711-1720. doi:10.1016/S0140-6736(04)16257-0

12. Xia J, Wishart DS. Using MetaboAnalyst 3.0 for Comprehensive Metabolomics Data Analysis. *Curr Protoc Bioinforma*. 2016;55:14.10.1-14.10.91. doi:10.1002/cpbi.11

13. Verdin E. NAD^+ in aging, metabolism, and neurodegeneration. *Science*. 2015;350(6265):1208-1213. doi:10.1126/science.aac4854

14. Zhang M, Ying W. NAD+ Deficiency Is a Common Central Pathological Factor of a Number of Diseases and Aging: Mechanisms and Therapeutic Implications. *Antioxid Redox Signal*. February 2018. doi:10.1089/ars.2017.7445

15. Mills KF, Yoshida S, Stein LR, et al. Long-Term Administration of Nicotinamide Mononucleotide Mitigates Age-Associated Physiological Decline in Mice. *Cell Metab*. 2016;24(6):795-806. doi:10.1016/j.cmet.2016.09.013

16. Yoshino J, Baur JA, Imai S-I. NAD+ Intermediates: The Biology and Therapeutic Potential of NMN and NR. *Cell Metab*. 2018;27(3):513-528. doi:10.1016/j.cmet.2017.11.002

17. Zhang H, Ryu D, Wu Y, et al. NAD^+ repletion improves mitochondrial and stem cell function and enhances life span in mice. *Science*. 2016;352(6292):1436-1443. doi:10.1126/science.aaf2693

18. Park JH, Long A, Owens K, Kristian T. Nicotinamide mononucleotide inhibits post-ischemic NAD(+) degradation and dramatically ameliorates brain damage following global cerebral ischemia. *Neurobiol Dis*. 2016;95:102-110. doi:10.1016/j.nbd.2016.07.018

19. Das A, Huang GX, Bonkowski MS, et al. Impairment of an Endothelial NAD + -H 2 S Signaling Network Is a Reversible Cause of Vascular Aging. *Cell*. 2018;173(1):74-89.e20. doi:10.1016/j.cell.2018.02.008

20. Williams PA, Harder JM, Cardozo BH, Foxworth NE, John SWM. Nicotinamide treatment robustly protects from inherited mouse glaucoma. *Commun Integr Biol*. 2018;11(1):e1356956. doi:10.1080/19420889.2017.1356956

21. Bocca C, Kouassi Nzoughet J, Leruez S, et al. A Plasma Metabolomic Signature Involving Purine Metabolism in Human Optic Atrophy 1 (*OPA1*)-Related Disorders. *Investig Opthalmology Vis Sci*. 2018;59(1):185. doi:10.1167/iovs.17-23027

22. Leruez S, Marill A, Bresson T, et al. A Metabolomics Profiling of Glaucoma Points to Mitochondrial Dysfunction, Senescence, and Polyamines Deficiency. *Investig Opthalmology Vis Sci*. 2018;59(11):4355. doi:10.1167/iovs.18-24938

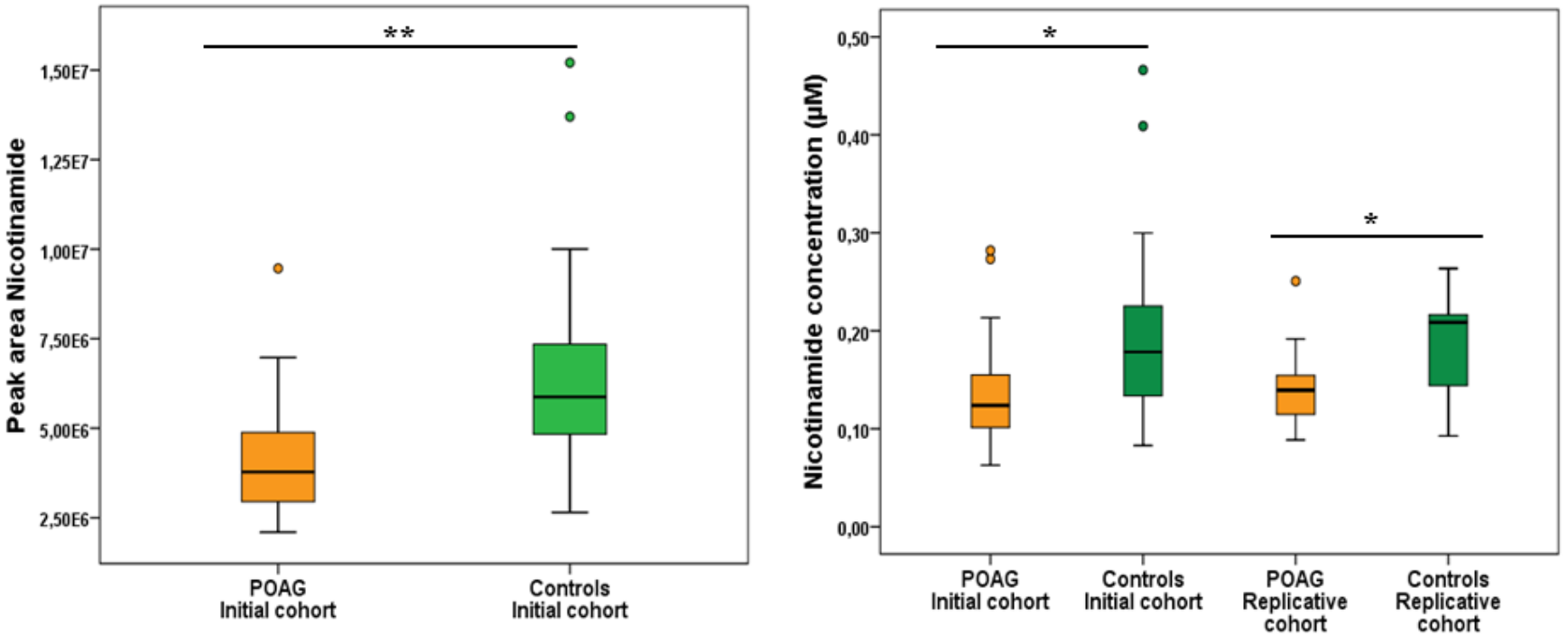

Figure: Boxplots showing nicotinamide levels in the initial (34 POAG and 30 control individuals) and replicative (20 POAG and 15 control individuals) cohorts. Error bars represent ± SEM, and the black bars within the boxplots represent the median concentration for each group. (Left) Peak area of nicotinamide found in the initial cohort following LC-HRMS analysis discloses a glaucoma/controls fold change of 0.65. (Right) Concentrations of nicotinamide found in the initial and replicative cohorts following LC-MS/MS analysis. The glaucoma/controls fold changes were 0.70 and 0.67 for the initial and replicative cohorts, respectively. The *p*-values between groups for all conditions were *: $p < 0.05$ and **: $p < 0.01$.

Table 1: Characteristics of individuals from the initial cohort. Demographic data and comorbidity status, systemic medications, ophthalmological features and glaucoma medication of individuals with POAG compared to controls. BMI: body mass index (weight/height^2). IOP: intraocular pressure; CCT: central corneal thickness; RNFL: retinal nerve fibre layer; VF-MD: visual field mean defect.

	POAG (N=34)	**Controls (N=30)**	***p*-value**
Demographic data and comorbidity			
Average age (y)	73.06	73.77	0.65
Females (%)	50	50	1
Mean BMI (kg/m^2)	26.22	26.99	0.59
Diabetes (%)	17.65	3.33	0.10
Hypertension (%)	50	63.33	0.29
Hyperlipidaemia (%)	26.47	43.33	0.165
Thyroid disease (%)	11.76	13.33	0.29
Systemic medications			
Anti-hypertensives (%)	47.06	63.33	0.19
Lipid-lowering medications (%)	23.53	43.33	0.09
Antiplatelet therapy (%)	26.47	36.67	0.39
Oral diabetes medications (%)	14.71	13.33	0.88
Insulin (%)	2.94	0	0.32
Corticosteroids (%)	2.94	3.33	0.93
Thyroid hormone (%)	17.65	13.33	0.64
Oestrogen (%)	0	0	1
Vitamin D (%)	11.76	20	0.38
Ophthalmological features and glaucoma medication			
Mean visual acuity (LogMar)	+0.12	+0.13	0.91
Mean IOP (mmHg)	13.42	14.10	0.27

Mean CCT (µm)	529.95	-	-
Average RNFL thickness (µm)	66.91	-	-
Mean VF-MD (dB),			
(eye with worse MD)	-6.83	-	-
Glaucoma severity (%)			
Mild	82.35	-	-
Moderate	5.88	-	-
Severe	11.77	-	-
Glaucoma medications (%)			
Beta-blockers	55.88	-	-
Prostaglandin analogue	67.65	-	-
Alpha-2-agonists	11.76	-	-
Carbonic anhydrase inhibitor	26.47	-	-

Table 2: Characteristics of individuals from the replicative cohort. Demographic data and comorbidity status, systemic medications, ophthalmological features and glaucoma medication of individuals with POAG compared to controls. BMI: Body mass index (weight/height^2). IOP: intraocular pressure; CCT: central corneal thickness; RNFL: retinal nerve fibre layer; VF-MD: visual field mean defect.

	POAG (N=20)	**Controls (N=15)**	***p*-value**
Demographic data and comorbidity			
Average age (y)	64.85	70.27	0.11
Females (%)	25	53.33	0.09
Mean BMI (kg/m^2)	25.75	28.27	0.30
Diabetes (%)	25	13.33	0.39
Hypertension (%)	35	73.33	0.02
Hyperlipidaemia (%)	25	60	0.04
Thyroid disease (%)	5	0	0.33
Systemic medications			
Anti-hypertensives (%)	35	73.33	0.02
Lipid-lowering medications (%)	25	60	0.04
Antiplatelet therapy (%)	25	13.33	0.39
Oral diabetes medications (%)	25	13.33	0.39
Insulin (%)	0	0	-
Corticosteroids (%)	5	0	0.33
Thyroid hormone (%)	5	0	0.33
Oestrogen (%)	0	0	-
Vitamin D (%)	10	6.67	0.73
Others (%)	40	33.33	0.69
Ophthalmological features and glaucoma medication			
Mean visual acuity (LogMar)	+0.05	+0.03	0.37
Mean IOP (mmHg)	15.82	13.84	<0.001

Mean CCT (µm)	544.44	-	-
Average RNFL thickness (µm)	68.7	-	-
Mean VF-MD (dB),			
(eye with worse MD)	-3.99	-	-
Glaucoma severity (%)			
Mild	80	-	-
Moderate	10	-	-
Severe	10	-	-
Glaucoma medications (%)			
Beta-blockers	60	-	-
Prostaglandin analogue	85	-	-
Alpha-2-agonists	0	-	-
Carbonic anhydrase inhibitor	15	-	-