

Bioenergetics in fibroblasts of patients with Huntington disease are associated with age at onset

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Neurol Genet 2018;4:e275. doi:10.1212/NXG.0000000000000275

Abstract

Objective

We aimed to assess whether differences in energy metabolism in fibroblast cell lines derived from patients with Huntington disease were associated with age at onset independent of the cytosine-adenine-guanine (CAG) repeat number in the mutant allele.

Methods

For this study, we selected 9 pairs of patients with Huntington disease matched for mutant CAG repeat size and sex, but with a difference of at least 10 years in age at onset, using the Leiden Huntington disease database. From skin biopsies, we isolated fibroblasts in which we (1) quantified the ATP concentration before and after a hydrogen-peroxide challenge and (2) measured mitochondrial respiration and glycolysis in real time, using the Seahorse XF Extracellular Flux Analyzer XF24.

Results

The ATP concentration in fibroblasts was significantly lower in patients with Huntington disease with an earlier age at onset, independent of calendar age and disease duration. Maximal respiration, spare capacity, and respiration dependent on complex II activity, and indices of mitochondrial respiration were significantly lower in patients with Huntington disease with an earlier age at onset, again independent of calendar age and disease duration.

Conclusions

A less efficient bioenergetics profile was found in fibroblast cells from patients with Huntington disease with an earlier age at onset independent of mutant CAG repeat size. Thus, differences in bioenergetics could explain part of the residual variation in age at onset in Huntington disease.

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Funding information and disclosures are provided at the end of the article. Full disclosure form information provided by the authors is available with the full text of this article at Neurology.org/NG.

The Article Processing charge was funded by the authors.

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Glossary

CAG = cytosine-adenine-guanine; **ECAR** = extracellular acidification rate; **OCR** = oxygen consumption rate.

Huntington disease, a devastating neurodegenerative disorder, is caused by an elongated cytosine-adenine-guanine (CAG) repeat sequence in exon 1 of the huntingtin gene (*HTT*).^{1–3} The length of the CAG repeat sequence accounts for 50%–70% of the variation in age at onset, leaving a substantial amount of unexplained variation, which could be attributed to genetic and environmental modifiers.^{4,5} In addition to progressive motor disturbances, neuropsychiatric symptoms, and cognitive decline, patients with Huntington disease and premanifest mutation carriers suffer from unintended weight loss.^{6,7} Recently, we demonstrated that this weight loss was associated with a faster rate of disease progression independent of CAG repeat number.⁸ Various evidence indeed indicates that disturbances in energy metabolism and mitochondrial defects play a role in Huntington disease pathology.^{9–11} Furthermore, mitochondrial metabolism was found to be impaired in peripheral tissues of patients with Huntington disease, including lymphoblastoid cell lines and skin fibroblasts.^{12–15} In support of the association between mitochondrial defects and Huntington disease symptomology, Huntington disease characteristics emerged in humans after accidental exposure to 3-nitropropionic acid (3-NP), a mitochondrial toxin that selectively inhibits the activity of mitochondrial complex II.^{16–19} However, to what extent differences in energy metabolism are associated with the onset of Huntington disease symptoms independent of the CAG repeat number is unknown. Therefore, the aim of our study was to investigate whether differences in energy metabolism were present in fibroblast cell lines from patients with Huntington disease with identical CAG repeat sizes but a large difference in age at onset.

Methods

Participants

From the Leiden Huntington disease database that contained data on 356 patients with Huntington disease, we selected 9 pairs of patients with Huntington disease older than 18 years, matched for sex and CAG repeat length, but with a large difference in age at onset, as defined by an expert neurologist (R.A.C.R.) based on motor, psychiatric, and/or cognitive symptoms. As a cutoff, we used a difference in age at onset of at least 10 years between each pair of patients. Aside from the age at onset derived from the date of clinical Huntington disease, we also noted the age at onset as estimated by the rater based on patient information and the age at onset of different Huntington disease symptoms (table 1). Exclusion criteria were presence of inflammatory diseases, an active infectious disease, and the use of anti-inflammatory or immunosuppressive drugs (e.g., non-steroidal anti-inflammatory drugs, and corticosteroids) or antioxidants (e.g., vitamin C) in

case temporary cessation of medication use (for about 7 times the drug's half-life) was not possible before sampling.

Standard protocol approvals, registrations, and patient consents

The study protocol was approved by the local ethics committee, and written informed consent was obtained from all participants.

Sampling and cell culture

During a regular visit to our outpatient clinic, we obtained phenotypic data and a small skin sample (i.e., 3 mm diameter) from the upper thigh of each participant via a punch biopsy. Fibroblasts from the skin samples were cultured in minimal essential medium (Gibco #10370-07) supplemented with 15% heat-inactivated fetal bovine serum (Gibco #10270106), 1% penicillin-streptomycin (10,000 U/mL, Gibco #15140122) and 1% GlutaMAX supplement (Gibco #35050061), and stored in a humidified incubator at 37°C with 5% CO₂. For the experiments described below, the fibroblasts were grown up to a maximum of 15 passages and harvested by trypsinization with trypsin-EDTA (0.05%, Gibco #25300054) at 37°C.

ATP concentration under oxidative stress

To assess whether bioenergetics differences in fibroblasts' response to oxidative stress between the matched pairs were present, we quantified the ATP concentration in the fibroblasts after subjecting them to 0.5 mM H₂O₂ for 0, 5, 10, and 15 minutes. In solid 96-well plates, we plated 12 replicates per cell line (i.e., 3 replicates per exposure period) with 30,000 cells in 100 μL regular culturing medium per well. Per plate, we included 14 blank wells (i.e., containing no cells) to which different ATP standard concentrations would later be added. Afterward, we incubated the plate for a minimum of 2 hours in a humidified incubator at 37°C with 5% CO₂ to allow the cells to attach.

We applied oxidative stress to the fibroblasts by replacing the regular culturing medium with a medium containing 0.5 mM H₂O₂ and 5% fetal bovine serum for the appointed stress periods.²⁰ To block the effect of H₂O₂ at the end of this period, we added catalase from bovine liver (50 U/mL medium, Sigma-Aldrich #C9322-1G)²⁰ and replaced the 0.5 mM H₂O₂ medium with 250 μL per well of the regular culturing medium.

We quantified the ATP concentration of the fibroblasts per well with the Luminescent ATP detection Assay Kit (Abcam #ab113849) and added different concentrations of the ATP standard (i.e., 0, 10, 100, 1,000, 10,000, 100,000, and 1,000,000 nM) provided by the kit to the blank wells. Luminescence was assessed with Perkin Elmer Multimode Plate Reader, Victor

Table 1 Age at onset of Huntington disease symptoms

Couple	CAG repeat number	Sex	Calendar age, y	Disease duration, y	Age at clinical diagnosis, y	Difference in age at clinical diagnosis, y	Age at symptom onset estimated by rater, y ^a	Difference in age at symptom onset estimated by rater, y ^a	Symptom at onset
1	41	F	55.0	8.6	46.4	24.7	46.4	21.7	m
	41	F	73.8	2.8	71.1		68.1		m
2	41	M	58.2	4.1	54.1	10.1	50.1	—	m, p
	41	M	67.4	3.2	64.3		—		m
3	42	F	52.9	7.8	45.1	28.2	45.1	26.2	p
	42	F	78.9	5.6	73.3		71.3		m
4	42	F	42.3	6.4	35.9	18.0	34.9	14.0	m
	42	F	59.8	5.9	53.9		48.9		m, p
5	42	M	43.5	6.6	36.9	23.9	35.9	21.9	p
	42	M	61.8	1.0	60.8		57.8		m, p
6	42	M	43.0	20.8	22.3	27.1	20.3	28.1	p
	42	M	52.0	2.7	49.3		48.3		m, c
7	45	M	43.5	2.2	41.3	15.2	34.3	12.2	p
	45	M	58.1	1.6	56.5		46.5		m
8	46	F	39.3	3.9	35.4	11.6	34.4	9.6	m, p, c
	46	F	49.9	2.9	47.0		44.0		c
9	46	M	49.0	16.0	33.0	14.0	33.0	13.0	p, c
	46	M	51.9	4.9	47.0		46.0		m
Average, y			54.5	5.9		19.2		18.3	

Abbreviations: c = cognitive symptom; CAG = cytosine-adenine-guanine; F = female; M = male; m = motor symptom; p = psychiatric symptom.

^a A medical doctor estimates the time at which the symptoms of the patient started based on the information provided by the patient and the patient's family.

X3. We quantified the ATP concentration per well by creating an ATP standard curve with a corresponding equation based on the luminescence per ATP standard. Using this standard curve equation, we determined the ATP concentration according to the average luminescence of the 3 wells per time point per cell line.

Mitochondrial respiration and glycolysis

Using the Seahorse XF Extracellular Flux Analyzer XF24, we could measure mitochondrial respiration and glycolysis simultaneously and in real time in our fibroblast cell lines. Respiration was measured as the oxygen consumption rate (OCR), and glycolysis was measured as the extracellular acidification rate (ECAR). In addition, the Seahorse allowed for the injection of 4 toxins during the experimental run and could monitor their effects over time. In succession, we injected the following toxins: 1 μ M oligomycin (ATP-synthase inhibitor); 1 μ M carbonyl cyanide-4-(trifluoromethoxy) phenylhydrazone (or carbonyl cyanide-p-trifluoromethoxy-phenyl-hydrazon [FCCP], oxidative phosphorylation uncoupler); 1M 3-nitropropionic acid (or

3-NP, complex II inhibitor), and 1 μ M antimycin A (complex III inhibitor). Fibroblasts were plated 1 day in advance of the experiment at 60,000 cells per well in a XF24 cell culture microplate. This density resulted in confluent cultures in which cell growth was blocked because of contact inhibition, avoiding potential biases because of different growth rates between fibroblast cell lines.²¹ On the day of the experiment, the regular fibroblast medium was removed, and the cells were washed twice with XF assay medium at 37°C, supplemented with 5 mM glucose and 1 mM sodium pyruvate, and the medium was buffered at pH 7.4. Subsequently, 675 μ L of the XF assay medium was added to each well, and the cells were incubated for 60 minutes in a 37°C incubator without CO₂ to allow the cells to equilibrate to the new medium.

During the experiment, 4 measurements were taken at baseline for both OCR and ECAR. Afterward, 3 measurements were taken after every toxin injection. From these values, we calculated 6 OCR parameters and 2 ECAR parameters. Basal respiration was defined as the average OCR values at baseline.

The average of the 3 OCR values after oligomycin injection was defined as the OCR due to proton leak. Maximal respiration was calculated by taking the average OCR of the 3 measurements after FCCP injection. The average OCR value after injection of 3-NP was defined as “respiration after 3-NP injection,” and the average respiration after antimycin A injection was defined as “non-mitochondrial respiration.” From these OCR parameters, another 3 parameters were calculated: respiration dedicated to ATP production (defined as basal respiration minus proton leak), spare capacity (defined as maximal respiration minus basal respiration), and respiration dependent on complex II activity (defined as maximal respiration minus respiration after 3-NP injection). Basal glycolysis was defined as the average ECAR of the 4 baseline ECAR measurements, and the increase in glycolysis after blocking ATP synthase was calculated by subtracting the basal glycolysis from the average ECAR after FCCP injection. To ensure that differences in the absolute averages were not due to variations in basal respiration and glycolysis, we also calculated the mitochondrial measurements as percentages of basal respiration and glycolysis.

Statistical analysis

To account for both the correlation within matched pairs, as well as the correlation due to serial measurements in time during each trial, we applied generalized linear mixed-effects models to analyze the results of the bioenergetics experiments. We set the calculated average ATP concentrations after oxidative stress of every cell line per time point as the target variable. Because of an exponential association between the ATP concentrations and time, we used the natural logarithmic transform of the index variable as the target variable. Group (i.e., earlier age at onset vs later age at onset), disease duration, calendar age at the time of biopsy, and time of exposure to H_2O_2 were included as fixed effects. Furthermore, we included a random intercept for each patient pair, as well as a random slope for time of exposure to H_2O_2 , to adequately account for both the matching between each pair of patients and the correlated measurements on each individual during the experiments. For mitochondrial respiration and glycolysis, we analyzed every calculated functional index separately. For each functional index, we defined the absolute OCR and ECAR or the relative OCR and ECAR as the target variables and constructed models as described above. For all models, we used an unstructured random effect covariance matrix and robust estimations of covariance, which result in consistent parameter estimates even if model assumptions are violated. All models were checked both graphically and analytically. All tests were 2-tailed, and the threshold for statistical significance (i.e., α) was set at 0.05. All analyses were performed in SPSS version 23.0 (IBM SPSS Statistics for Windows, IBM Corp).

Data availability

Additional data will be made available at the request of other investigators.

Results

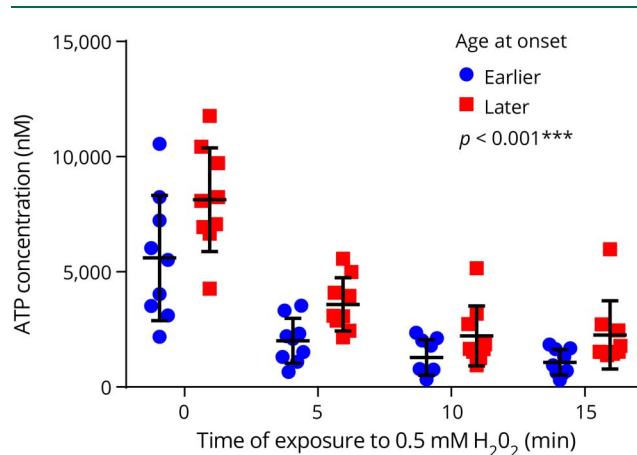
Differences in age at onset

The age at onset in the 18 selected patients with Huntington disease ranged between 22 and 73 years, and the average difference in age at onset between patient pairs was 19.2 years. The patient pairs had CAG repeat sequences between 41 and 46 repeats, and 5 of the 9 pairs were men. Furthermore, the symptoms at onset of disease varied per patient between motor, psychiatric, and cognitive symptoms (table 1).

ATP concentrations were lower in the skin fibroblasts of patients with Huntington disease with an earlier age at onset

In all fibroblast cell lines, the ATP concentration decreased over the time exposed to 0.5 mM H_2O_2 . The decrease was exponential (figure 1 and figure e-1, links.lww.com/NXG/A84). Therefore, we used the natural logarithmic transform of the ATP concentration (\ln ATP) as the target variable in the analysis. We found that \ln ATP was significantly lower in patients with an earlier age at onset compared with the matched patients with a later age at onset (figure 1 and table 2). This difference was present at baseline in 7 of the 9 couples and continued to be evident throughout the period the cells were subjected to oxidative stress in 7 couples (figure e-1). Because the difference in age at onset as estimated by the rater was missing in couple number 2, causing the data of this couple to be less reliable (table 1), we performed a sensitivity analysis by excluding these patients. Exclusion of these patients from the analysis did not materially alter our results (table 2).

Figure 1 Average ATP concentration in the skin fibroblasts of patients with Huntington disease exposed to oxidative stress over time



In all fibroblast cell lines, the average ATP concentration decreased exponentially as the time exposed to oxidative stress increased. At every time point, the group of patients with an earlier age at onset had a lower ATP concentration compared with the group of patients with a later age at onset. $p < 0.001***$ indicates the significant effect of group (i.e., earlier or later age at onset) on the ATP concentration determined using linear mixed-effects models. Error bars indicate \pm SD.

Table 2 Association between the logarithmic transform of the average ATP concentration and earlier vs later age at onset in HD

Analysis	Fixed effects	β -coefficient ^a	SE	t	p Value	95% CI	
All cases	Group (earlier)	-0.709	0.177	-4.00	<0.001***	-1.063	-0.355
	Disease duration	0.016	0.025	0.66	0.511	-0.033	0.066
	Calendar age	0.000	0.010	-0.04	0.969	-0.021	0.020
	Time	-0.102	0.008	-13.01	<0.001***	-0.118	-0.087
Sensitivity analysis^b	Group (earlier)	-0.642	0.255	-2.52	0.015*	-1.153	-0.132
	Disease duration	0.013	0.027	0.50	0.619	-0.040	0.067
	Calendar age	0.000	0.011	0.03	0.978	-0.021	0.021
	Time	-0.101	0.009	-11.56	<0.001***	-0.119	-0.084

Abbreviation: CI = confidence interval.

* $p < 0.05$, *** $p < 0.001$.

^a This column indicates the change in logarithmic transform of the ATP concentration.

^b The analysis excluding patient pair number 2 (table 1).

Mitochondrial indices were lower in the skin fibroblasts of patients with Huntington disease with an earlier age at onset

The average OCR and the ECAR per Huntington disease patient group during the experiment are presented in figure e-2, links.lww.com/NXG/A84. Neither the absolute mitochondrial parameters nor the parameters expressed as percentage of basal respiration differed significantly per group before correction for disease duration and calendar age (figure e-3). However, after correction, we found the absolute OCR averages to be significantly different between the 2 groups in 4 of the 8 estimated parameters (table 3). The average maximal respiration was lower in the group of patients with Huntington disease with an earlier age at onset. All 9 patients with an earlier age at onset had a lower maximal respiration compared with the matched patients with a later age at onset. Similarly, in 8 of the 9 couples, the spare capacity was lower in the earlier age at onset group. Furthermore, the respiration dedicated to ATP production (in 6 couples) and the respiration dependent on complex II activity (in 8 couples) were significantly lower in the group of patients with Huntington disease with an earlier age at onset. The average basal respiration was not markedly different between the 2 groups. Average OCR as a percentage of the basal respiration differed in 3 parameters between the groups, including maximal respiration (in 8 couples), spare capacity (in 8 couples), and respiration dependent on complex II activity (in 9 couples). No difference in average respiration dedicated to ATP production was found when this variable was defined as a percentage of basal respiration. The glycolysis parameters did not differ between the groups, although the difference in basal glycolysis showed a trend toward statistical significance in which the group of patients with Huntington disease with an earlier age at onset had a lower average basal ECAR. To illustrate these effects, we plotted the unadjusted values, as well as the predicted values, calculated using the model estimates after

adjustment for disease duration and calendar age (figure 2A-I, and figure e-3). The effects did not change after excluding couple 2 in the sensitivity analysis (table 4).

Of interest, disease duration and calendar age were also significantly associated with several indices of mitochondrial bioenergetics. Longer disease duration was accompanied by lower absolute values of basal respiration, maximal respiration, respiration after 3-NP injection, respiration dependent on complex II activity, and glycolysis after blocking ATP synthase. Furthermore, patients with a higher calendar age had significantly lower levels of maximal respiration, respiration dedicated to ATP production, spare capacity, respiration dependent on complex II activity, basal glycolysis, and glycolysis after blocking ATP synthase. In addition, the parameters maximal respiration, spare capacity, and respiration dependent on complex II activity were also significantly lower with a higher calendar age when expressed as percentages of the basal respiration (table 3).

Discussion

We found lower ATP concentrations in the skin fibroblasts of patients with Huntington disease with an earlier age at onset compared with those with a later age at onset, independent of CAG repeat number, sex, calendar age, and disease duration. In addition, we demonstrated that the fibroblasts of patients with Huntington disease with an earlier age at onset exhibited lower mitochondrial respiration indices, including lower maximal respiration, spare capacity, and respiration dependent on complex II activity in an absolute sense, as well as relative to their basal respiration levels. Furthermore, we found that disease duration and age at biopsy were also significantly associated with several parameters of mitochondrial bioenergetics. Although mitochondrial defects have been extensively documented before in Huntington disease, to our knowledge, we are the first to demonstrate that differences in

Table 3 Association between the calculated mitochondrial stress test parameters and age at onset in Huntington disease

Measurement	Output	Variable	β -coefficient ^a	SE	t	p Value	95% CI	
Basal respiration	OCR	Group (earlier)	-4.520	18.249	-0.25	0.808	-43.661	34.621
		Disease duration	-1.799	0.650	0.02	0.015	-3.193	-0.405
		Calendar age	0.194	0.566	0.74	0.737	-1.020	1.409
Proton leak	OCR	Group (earlier)	-14.298	11.319	-1.26	0.227	-38.575	9.979
		Disease duration	0.143	0.472	0.30	0.766	-0.869	1.156
		Calendar age	-0.343	0.435	-0.79	0.443	-1.275	0.589
	%OCR	Group (earlier)	-6.784	8.820	-0.77	0.455	-25.701	12.133
		Disease duration	0.807	0.475	1.70	0.112	-0.213	1.826
		Calendar age	-0.174	0.378	-0.46	0.652	-0.984	0.636
Maximal respiration	OCR	Group (earlier)	-54.176	17.454	-3.10	0.008**	-91.610	-16.741
		Disease duration	-3.317	0.822	-4.04	0.001**	-5.080	-1.554
		Calendar age	-2.118	0.818	-2.59	0.021*	-3.872	-0.365
	%OCR	Group (earlier)	-46.730	20.325	-2.30	0.037*	-90.321	-3.138
		Disease duration	-0.430	0.930	-0.46	0.651	-2.426	1.565
		Calendar age	-2.577	0.949	-2.72	0.017*	-4.613	-0.542
Respiration after 3-NP injection	OCR	Group (earlier)	-17.226	9.145	-1.88	0.081	-36.839	2.387
		Disease duration	-1.277	0.421	-3.03	0.009**	-2.180	-0.374
		Calendar age	-0.529	0.259	-2.05	0.060	-1.084	0.025
	%OCR	Group (earlier)	-5.133	8.749	-0.59	0.567	-23.898	13.632
		Disease duration	-0.527	0.459	-1.15	0.269	-1.511	0.456
		Calendar age	-0.453	0.565	-0.80	0.436	-1.664	0.758
Nonmitochondrial respiration	OCR	Group (earlier)	-12.355	9.515	-1.30	0.215	-32.763	8.053
		Disease duration	0.699	0.434	1.61	0.129	-0.231	1.629
		Calendar age	-0.139	0.386	-0.36	0.723	-0.968	0.689
	%OCR	Group (earlier)	-0.607	8.521	-0.07	0.944	-18.881	17.668
		Disease duration	0.933	0.503	1.85	0.085	-0.146	2.013
		Calendar age	0.292	0.344	0.85	0.411	-0.446	1.030
Respiration dedicated to ATP production	OCR	Group (earlier)	-38.106	11.243	-3.39	0.004**	-62.219	-13.992
		Disease duration	0.936	0.655	0.1.43	0.175	-0.468	2.341
		Calendar age	-1.818	0.450	-4.04	0.001**	-2.783	-0.852
	%OCR	Group (earlier)	6.784	8.820	0.46	0.455	-12.133	25.701
		Disease duration	-0.807	0.475	-1.70	0.112	-1.826	0.213
		Calendar age	0.174	0.378	0.46	0.652	-0.636	0.984

Continued

Table 3 Association between the calculated mitochondrial stress test parameters and age at onset in Huntington disease (continued)

Measurement	Output	Variable	β -coefficient ^a	SE	t	p Value	95% CI	
Spare capacity	OCR	Group (earlier)	-50.884	9.894	-5.14	<0.001***	-72.104	-29.663
		Disease duration	-1.482	0.700	-2.12	0.053	-2.984	0.019
		Calendar age	-2.387	0.685	-3.48	0.004**	-3.856	-0.918
	%OCR	Group (earlier)	-46.730	20.325	-2.30	0.037*	-90.321	-3.138
		Disease duration	-0.430	0.930	-0.46	0.651	-2.426	1.565
		Calendar age	-2.577	0.949	-2.72	0.017*	-4.613	-0.542
Respiration dependent on complex II activity	OCR	Group (earlier)	-36.950	13.397	-2.76	0.015*	-65.685	-8.216
		Disease duration	-2.039	0.598	-3.41	0.004**	-3.323	-0.756
		Calendar age	-1.589	0.597	-2.66	0.019*	-2.868	-0.309
	%OCR	Group (earlier)	-31.122	12.292	-2.53	0.024*	-57.486	-4.759
		Disease duration	-0.737	0.415	-1.78	0.097	-1.627	0.153
		Calendar age	-1.683	0.520	-3.24	0.006**	-2.797	-0.569
Basal glycolysis	ECAR	Group (earlier)	-5.404	2.763	-1.96	0.071	-11.331	0.523
		Disease duration	-0.330	0.193	-1.71	0.110	-0.745	0.085
		Calendar age	-0.447	0.129	-3.46	0.004**	-0.724	-0.170
Glycolysis after blocking ATP-synthase	ECAR	Group (earlier)	0.614	3.302	0.19	0.855	-6.468	7.697
		Disease duration	-0.643	0.153	-4.20	0.001**	-0.971	-0.314
		Calendar age	-0.187	0.079	-2.38	0.032*	-0.356	-0.019
	%ECAR	Group (earlier)	48.604	25.707	1.891	0.080	-6.532	103.739
		Disease duration	-0.010	2.250	-0.004	0.997	-4.835	4.816
		Calendar age	4.988	2.202	2.266	0.040*	0.267	9.710

Abbreviations: CI = confidence interval; ECAR = extracellular acidification rate; %ECAR = ECAR as a percentage of basal ECAR; OCR = oxygen consumption rate; %OCR = OCR as a percentage of basal OCR.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

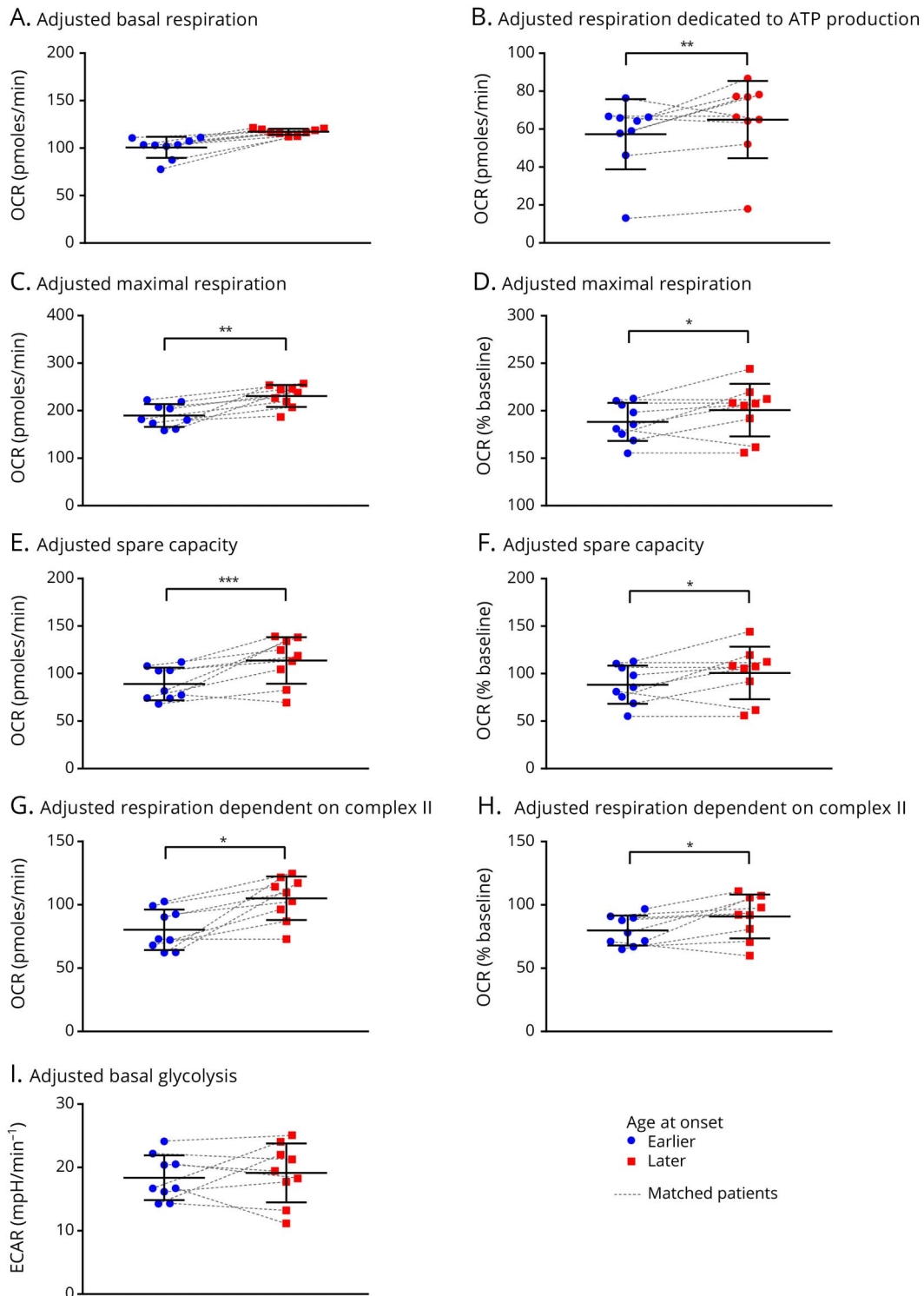
^a This column indicates the change in OCR, ECAR, %OCR, or %ECAR.

bioenergetics were associated with age at onset among patients with Huntington disease, and thereby, could be an important target for future therapeutic interventions.

The fact that the ATP concentration was lower in patients with Huntington disease with an earlier age at onset suggests that the production of ATP in the cells of these patients may be impaired to a greater extent compared with their counterparts or that the cells of patients with a later age at onset carry a mechanism that protects their ATP metabolism. The presence of a potential problem with ATP production was supported by comparable differences in various indices of

mitochondrial respiration. Maximal respiration and mitochondrial spare capacity are measures of the ability of mitochondria to react to increased energy demands and are critical for neuronal survival.^{22–24} These measures were lower in patients with an earlier age at onset, suggesting that neurons in these patients could be more vulnerable to damage and death, thus causing Huntington disease symptoms to start at a younger age. Of interest, a previous study showed a correlation between decreased levels of spare capacity and increased reactive oxygen species and mitochondrial DNA lesions in mutant Huntington disease striatal immortalized neuronal cells.¹⁵ Respiration dependent on complex II activity was also

Figure 2 Adjusted estimates of the functional indices calculated from the mitochondrial stress test per age group at symptom onset in Huntington disease



There was no difference in basal respiration between the 2 groups (A). The absolute mitochondrial respiration dedicated to ATP production was significantly lower in the group of patients with Huntington disease with an earlier age at onset (B). Both the absolute maximal respiration and the maximal respiration as a percentage of the basal respiration were significantly lower in the group of patients with Huntington disease with an earlier age at onset (C and D). The absolute spare capacity and the spare capacity as a percentage of the basal respiration were significantly lower in the group of patients with Huntington disease with an earlier age at onset (E and F). The absolute respiration dependent on complex II activity and the respiration dependent on complex II activity as a percentage of the basal respiration were also significantly lower in the group of patients with Huntington disease with an earlier age at onset (G and H). The basal glycolysis did not differ significantly between the 2 groups (I). Adjusted estimates = values adjusted for disease duration and calendar age at the time of biopsy. Error bars indicate \pm SD. * p -value < 0.05. ** p -value < 0.01. *** p -value < 0.001. ECAR = extracellular acidification rate; OCR = oxygen consumption rate.

Table 4 Sensitivity analysis of the association between the mitochondrial stress test parameters and age at onset in Huntington disease

Measurement ^a	Output	Variable	β -coefficient ^b	SE	t	p Value	95% CI	
Maximal respiration	OCR	Group (earlier)	-56.810	24.570	-2.31	0.039*	-110.343	-3.277
		Disease duration	-2.938	1.079	-2.72	0.018*	-5.288	-0.588
		Calendar age	-2.815	0.568	-4.96	<0.001***	-4.053	-1.577
	%OCR	Group (earlier)	-56.330	24.401	-2.31	0.040*	-109.495	-3.164
		Disease duration	0.018	0.965	0.02	0.985	-2.084	2.120
		Calendar age	-2.903	1.061	-2.74	0.018*	-5.215	-0.591
Respiration dedicated to ATP production	OCR	Group (earlier)	-31.600	9.310	-3.39	0.005**	-51.884	-11.315
		Disease duration	0.619	0.506	1.22	0.245	-0.483	1.721
		Calendar age	-1.684	0.396	-4.25	0.001**	-2.547	-0.821
	%OCR	Group (earlier)	15.130	7.065	2.14	0.053	-0.263	30.523
		Disease duration	-1.186	0.328	-3.61	0.004**	-1.901	-0.471
		Calendar age	0.482	0.312	1.55	0.148	-0.197	1.162
Spare capacity	OCR	Group (earlier)	-56.929	11.504	-4.95	<0.001***	-81.995	-31.863
		Disease duration	-1.066	0.619	-1.72	0.111	-2.414	0.283
		Calendar age	-2.825	0.556	-5.08	<0.001***	-4.037	-1.613
	%OCR	Group (earlier)	-56.330	24.401	-2.31	0.040*	-109.495	-3.164
		Disease duration	0.018	0.965	0.02	0.985	-2.084	2.120
		Calendar age	-2.903	1.061	-2.74	0.018*	-5.215	-0.591
Respiration dependent on complex II activity	OCR	Group (earlier)	-39.637	17.613	-2.25	0.044*	-78.012	-1.261
		Disease duration	-1.773	0.790	-2.24	0.045*	-3.495	-0.051
		Calendar age	-2.015	0.483	-4.17	0.001**	-3.067	-0.962
	%OCR	Group (earlier)	-35.371	14.785	-2.39	0.034*	-67.584	-3.157
		Disease duration	-0.522	0.465	-1.12	0.284	-1.535	0.492
		Calendar age	-1.866	0.559	-3.34	0.006**	-3.083	-0.649

Abbreviations: CI = confidence interval; ECAR = extracellular acidification rate; %ECAR = ECAR as a percentage of basal ECAR; OCR = oxygen consumption rate; %OCR = OCR as a percentage of basal OCR.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

^a Analyses performed with exclusion of couple number 2.

^b This column indicates the change in OCR, ECAR, %OCR, or %ECAR.

lower in patients with Huntington disease with an earlier age at onset. Different studies showed that in postmortem samples of the striatum and cerebral cortex of patients with Huntington disease, complex II of the mitochondrial electron transport chain displayed reduced activity, which was associated with diminished expression of 2 complex II subunits.^{25–29} The exact mechanism as to how the mutated huntingtin protein (HTT)

causes the loss of complex II is unknown. Possible hypotheses include the direct association of mutant HTT with the mitochondrial membrane, causing decreased import of subunits into the mitochondria, increased degradation, or abnormal assembly.^{13,29,30} Furthermore, mutant HTT has been shown to increase cellular oxidative stress, which was associated with impaired activity of complex II in a yeast model of Huntington

disease.^{31–33} Our results here suggest that the reduced expression of complex II is more pronounced in patients with an earlier age at onset independent of CAG repeat length, which could perhaps be due to a more potent association of mutant HTT with the mitochondrial membrane or a higher vulnerability to oxidative stress.

Candidate studies found that a single nucleotide polymorphism in *PPARGCIA*, encoding the mitochondrial regulator peroxisome proliferator-activated receptor gamma coactivator-1 α (PGC-1 α), affected the age at onset in 3 European Huntington disease cohorts, suggesting that our findings might have a genetic origin.^{34,35} Moreover, in striata from patients with Huntington disease and different rodent Huntington disease models, the expression of PGC-1 α mRNA was reduced, and upregulating this expression caused prevention of striatal neuronal atrophy, improvement of motor deficits, and protection against mitochondrial dysfunction and cell death, implying that PGC-1 α expression may modify mutant HTT-induced mitochondrial toxicity.^{36–38} Together with our results, these findings indicate that differences in PGC-1 α expression and the consequential variations in bioenergetics profile may result in additional variation in age at onset in Huntington disease.

We found that as patients suffered from Huntington disease for a longer period of time, several indices of mitochondrial respiration were significantly lower, independent of calendar age. This finding is in line with the fact that Huntington disease pathogenesis is known to involve mitochondrial deficits.^{39,40} Therefore, a reasonable derivative is that these mitochondrial deficits become worse as the disease progresses. Mitochondrial function is also known to decrease with age.⁴¹ In accordance, we found that as the calendar age of patients increased, several parameters of mitochondrial function decreased. The aging process itself is unlikely to have accounted for our main finding (i.e., a better bioenergetics profile in late-onset patients), given that patients with a later age at onset were older at the time of biopsy (table 1).

Our study had several limitations. First, although Huntington disease is primarily a neurologic disease, we were able to find differences between patients with Huntington disease with an early onset and late onset of symptoms in skin fibroblasts. The fact that we could acquire relevant results in these relatively easy to obtain cells is intriguing and supports the use of fibroblast cell models in the research of neurodegenerative diseases. However, these cells are not the primary cells of interest. Therefore, repeating similar experiments in a neuronal cell model, such as striatal neurons derived from induced pluripotent stem cells, is warranted. Second, establishing the age at onset in Huntington disease is subjective.⁴² In order to achieve additional certainty concerning this age, we noted the age at Huntington disease diagnosis, as well as the age estimated by the rater, which were analogous in 8 of the 9 couples. In addition, our results did not change after excluding the couple in which the rater-estimated age at onset was missing for 1 patient, illustrating that our results are robust and

reliable. Last, we performed several statistical analyses without applying a correction for multiple testing, given our relatively small sample size, as well as the fact that bioenergetics assessments are highly correlated and, thus, cannot be regarded as independent. Nevertheless, to obtain results with a higher level of confidence, future research investigating similar parameters should include a larger number of patients.

We demonstrated an association between age at onset and the bioenergetics profile in patients with Huntington disease. Thus, differences in bioenergetics could explain part of the residual variation in age at onset among patients with Huntington disease, whereas therapies aimed at enhancing mitochondrial function may delay disease onset. However, further research into the mechanisms mediating the association between bioenergetics and age at onset are needed to develop novel therapies aimed at delaying symptom onset and disease progression in Huntington disease.

Author contributions

S.L. Gardiner and N.A. Aziz contributed to the conception and design of the study and to the acquisition and analysis of data. C. Milanese and W.M.C. van Roon-Mom offered crucial supervision during the experiments. All authors contributed to drafting the text and preparing the figures.

Acknowledgment

The authors cordially thank all patients and caregivers involved in the experiments for their valuable time and efforts. The authors also thank Ms. L.J. Schipper, M.D., for assistance in taking skin biopsies.

Study funding

NAA is supported by a VENI-grant (#91615080) from the Netherlands Organization for Scientific Research and a Marie Skłodowska-Curie Individual Fellowship grant from the European Union (Horizon 2020, #701130).

Disclosure

S. Gardiner, C. Milanese, M.W. Boogaard, R.A.M. Buijsen, and M. Hogenboom report no disclosures. R.A.C. Roos is a consultant for uniQure. P.G. Mastroberardino serves on the editorial boards of *Neurobiology of Disease*, *Frontiers in Cellular Neuroscience*, and *Cell Death and Disease*; is a consultant for the Neurological Institute; and has received research support from Dorpmans-Wigmans Stichting. W.M.C. van Roon-Mom has served on the medical advisory board of the ADCA Patients' Association; is the main inventor on 2 published patent applications (WO2012/018257 and WO2015/053624) regarding exon skipping approaches for neurodegenerative diseases; and is coinventor on 1 published patent application on exon skipping approaches for SCA3 (WO 2017/053781). N.A. Aziz has received research support from the Netherlands Organization for Scientific Research (NWO), the European Union, and the European Huntington's Disease Network. Full disclosure form information provided by the authors is available with the full text of this article at Neurology.org/NG.

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Neurol Genet 2018;4;

DOI 10.1212/NXG.0000000000000275

This information is current as of October 4, 2018

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