The mitochondrial energy transduction system and the aging process

Ana Navarro¹ and Alberto Boveris²

¹Department of Biochemistry and Molecular Biology, School of Medicine, University of Cádiz, Cádiz, Spain; and ²School of Pharmacy and Biochemistry, University of Buenos Aires, Buenos Aires, Argentina

Navarro A, Boveris A. The mitochondrial energy transduction system and the aging process. Am J Physiol Cell Physiol 292: C670–C686, 2007; doi:10.1152/ajpcell.00213.2006.—Aged mammalian tissues show a decreased capacity to produce ATP by oxidative phosphorylation due to dysfunctional mitochondria. The mitochondrial content of rat brain and liver is not reduced in aging and the impairment of mitochondrial function is due to decreased rates of electron transfer by the selectively diminished activities of complexes I and IV. Inner membrane 

H⁺ impermeability and F₁-ATP synthase activity are only slightly affected by aging. Dysfunctional mitochondria in aged rodents are characterized, besides decreased electron transfer and O₂ uptake, by an increased content of oxidation products of phospholipids, proteins and DNA, a decreased membrane potential, and increased size and fragility. Free radical-mediated oxidations are determining factors of mitochondrial dysfunction and turnover, cell apoptosis, tissue function, and lifespan. Inner membrane enzyme activities, such as those of complexes I and IV and mitochondrial nitric oxide synthase, decrease upon aging and afford aging markers. The activities of these three enzymes in mice brain are linearly correlated with neurological performance, as determined by the tightrope and the T-maze tests. The same enzymatic activities correlated positively with mice survival and negatively with the mitochondrial content of lipid and protein oxidation products. Conditions that increase survival, as vitamin E dietary supplementation, caloric restriction, high spontaneous neurological activity, and moderate physical exercise, ameliorate mitochondrial dysfunction in aged brain and liver. The pleiotropic signaling of mitochondrial H₂O₂ and nitric oxide diffusion to the cytosol seems modified in aged animals and to contribute to the decreased mitochondrial biogenesis in old animals.

ADP addition and identified the sites that are thermodynamically and kinetically compatible with energy transduction.

The knowledge of ATP synthase followed contributions from morphology and biochemistry. Electron microscopy of heart mitochondria by Fernandez-Moran (52) revealed regularly spaced “elementary particles” of 8–10 nm diameter, later identified as the F₁ subunit of ATP synthase. The properties of ATP-synthase, called F₁-ATPase at that time, were described by the work of Racker and co-workers (130) and of Boyer (18). The modern knowledge of the vectorial biochemistry of mitochondrial energy transduction was developed after the formulation of Mitchell’s chemiosmotic theory (106, 107). The subsequent landmark contribution of Walker (156) was the understanding of the mechanism of ATP synthesis by the molecular rotor driven by proton (H⁺) flow through the ATP synthase complex.

We now understand oxidative phosphorylation as a process catalyzed by constitutive proteins of the inner mitochondrial membrane that encompasses electron transfer between the complexes of the respiratory chain, vectorial H⁺ release into the intermembrane space, and H⁺ reentry to the matrix through F₀ with ATP synthesis by the F₁-ATP synthase. In addition, mitochondria are recognized to contribute to intracellular signaling and regulation with a central role in keeping homeostatic cell ionic composition (44).

EARLY OBSERVATIONS by Leloir and Muñoz (92) indicated that fatty acid oxidation depends on a labile particulate material of liver homogenates. Later, Kennedy and Lehninger (82) reported that the oxidation of fatty acids and of citric acid cycle intermediates was carried out by osmotically active structures with coupled ADP phosphorylation to ATP. Simultaneously, Sjostand (146) and Palade (126) recognized by electron microscopy the characteristic double membrane of mitochondria. The concept of oxidative phosphorylation as the mitochondrial function evolved from the confluence of structural and biochemical knowledge and by 1952, mitochondria were described by Lehninger (91) as intracellular “power plants”.

BIOLOGICAL ENERGY TRANSDUCTION: INTRODUCTION AND HISTORICAL PERSPECTIVE

The isolation of mitochondrial proteins with specific electron transfer properties by Green and co-workers provided the concept of “complexes” of the respiratory chain (65) By 1955, Chance and co-workers (32), by using spectrophotometric techniques, described the reduction-oxidation levels of the components of the respiratory chain in the transition following ADP addition and identified the sites that are thermodynamically and kinetically compatible with energy transduction.

The knowledge of ATP synthase followed contributions from morphology and biochemistry. Electron microscopy of heart mitochondria by Fernandez-Moran (52) revealed regularly spaced “elementary particles” of 8–10 nm diameter, later identified as the F₁ subunit of ATP synthase. The properties of ATP-synthase, called F₁-ATPase at that time, were described by the work of Racker and co-workers (130) and of Boyer (18). The modern knowledge of the vectorial biochemistry of mitochondrial energy transduction was developed after the formulation of Mitchell’s chemiosmotic theory (106, 107). The subsequent landmark contribution of Walker (156) was the understanding of the mechanism of ATP synthesis by the molecular rotor driven by proton (H⁺) flow through the ATP synthase complex.

We now understand oxidative phosphorylation as a process catalyzed by constitutive proteins of the inner mitochondrial membrane that encompasses electron transfer between the complexes of the respiratory chain, vectorial H⁺ release into the intermembrane space, and H⁺ reentry to the matrix through F₀ with ATP synthesis by the F₁-ATP synthase. In addition, mitochondria are recognized to contribute to intracellular signaling and regulation with a central role in keeping homeostatic cell ionic composition (44).
The Mitochondrial Membranes

Mitochondria are characterized by two membranes, the inner and the outer membranes, with two compartments separated by the inner membrane. Cristae are invaginations of the inner membrane and the intermembrane and intracristal spaces are continuous and form a single compartment. The matrix, surrounded by the folding of the inner membrane, comprises the second compartment (126, 146).

The outer mitochondrial membrane is permeable to small molecules and ions, which move through transmembrane channels formed by a family of integral membrane proteins called porins. Voltage-dependent anion channels are the potential-sensitive porins of the outer membrane that allow metabolite exchange between mitochondria and the cytoplasm (67).

The inner membrane is impermeable to H⁺ and this property provides the basis of mitochondrial energy transduction. Chemical species as ions and small molecules that cross the inner membrane have specific transporters. The inner membrane bears, as integral proteins, the key catalysts of oxidative phosphorylation: the electron transfer respiratory complexes and the ATP synthase complex (106).

Components of Mitochondrial Respiratory Chain and Respiratory Assemblies

The mitochondrial respiratory chain consists of a series of electron carriers that function as redox pairs and that are mainly prosthetic groups of integral proteins. There are four electron transfer or respiratory complexes (complexes I–IV), each capable of catalyzing electron transfer in a partial reaction of the respiratory chain.

Complex I (NADH-ubiquinone oxidoreductase; NADH dehydrogenase) is composed of 42–43 different polypeptides, including a FMN-containing flavoprotein and 6 iron-sulfur centers (73, 74). Complex I has an L-shaped form, with the long arm as a hydrophilic integral membrane protein and the short arm extending into the matrix with the hydrophilic part that contains the FMN and the NADH active center (56). The two arms of the L-shaped complex I have separated genetic origin and independent assembly (75).

Rotenone is the specific and stoichiometric inhibitor of complex I in mitochondrial fragments and in isolated mitochondria (33). Some complex I preparations, obtained by membrane solubilization or by further resolution of the classic rotenone-sensitive Hatefi’s complex I (73), catalyze rotenone-insensitive NADH oxidation by artificial electron acceptors (93). It is understood that all rotenone-insensitive NADH dehydrogenase preparations are denatured forms of complex I, a point that illustrates the convenience of using native preparations in the assessment of complex I dysfunction in aging and neurological diseases.

Ubiquinone is a lipid soluble benzoquinone with a long isoprenoid side chain that is laterally diffusible in each of the two layers of the phospholipid bilayer of the inner membrane and adapted to shuttle electrons between membrane proteins. Complex I, prepared by the Hatefi’s procedure, contains ~4 mol of ubiquinone per mol of FMN (74).

Complex II (succinate dehydrogenase; succinate-ubiquinone reductase) is the membrane-bound component of the citric acid cycle that also functions as a component of the mitochondrial respiratory chain. The integral protein has a covalently bound FAD and iron-sulfur centers in the membrane extrinsic domain that catalyze electron transfer to ubiquinone and b heme in the hydrophobic membrane domain (28).

Complex III (cytochrome bc₁ complex; ubiquinol-cytochrome c oxidoreductase) is composed of 9–10 polypeptides, 3 of which are associated with redox centers. These centers are b₅₆₂, b₅₆₆, and c₁ hemes and a [2Fe-2S] cluster (73). In addition, two ubisemiquinone bind to two separate domains of complex III (42).

Cytochrome c is a peripheral protein facing the intermembrane space, easily solubilized by salt treatments, that transfers electrons from complex III to the Cu₄ of complex IV.

Complex IV (cytochrome c oxidase, cytochrome oxidase; cytochrome c-O₂ oxidoreductase) is the final catalyst of the respiratory chain. Complex IV reduces O₂ to H₂O with four electrons from reduced cytochrome c in a process that consumes 4 H⁺ from the matrix. It is worth noting that complex IV dysfunction is common in aging and in neurological diseases.

The stoichiometry of the complexes of the respiratory chain is an interesting subject of current studies. The spectrophotometric determination of the respiratory carriers in isolated mitochondria (32) and the determination of the content of respiratory complexes in mitochondrial fragments prepared by sonic or chemical treatments (65) showed that they occur in simple molar ratios. This finding indicates that respiratory carriers and complexes are arranged in “assemblies” with specific protein-protein interactions, which are effective for rapid electron transfer by limiting the intermolecular distances that slow-diffusing proteins should otherwise travel between collisions (32). A single liver mitochondrion contain ~10,000 complete respiratory assemblies, the number is higher in kidney and about twice in heart mitochondria.

Complexes I, III, and IV interact to form supercomplexes with defined stoichiometric composition in mitochondria from yeast, higher plants, and mammals. Supercomplexes I₁III₂ and I₁III₃IV₁ were reported in bovine heart mitochondria (140).

Oxidation and electrochemical potentials in the mitochondrial respiratory chain

The electron flow from the electron donors, NADH or succinate, to the acceptor, O₂, occurs following the oxidation potential of the components of the electron transfer chain. Electrons move toward compounds with more positive oxidation potentials as given by the standard redox potential and the ratio of the oxidized and reduced forms, according to the Nernst equation. The differences in redox potential of the electron carriers define the reactions that are exergonic enough to provide the free energy required for the coupled endergonic pumping of H⁺ into the intermembrane space.

Complexes I, III, and IV function as H⁺ pumps, acting in series with respect to electron flux and in parallel with respect to the H⁺ circuit. The H⁺ pumps are driven by the free energy of the coupled oxidation reactions and have the characteristic that the catalyzed oxidation and the H⁺ release are both vectorial and coupled. The movements of H⁺ occur in a specific direction from the matrix to the intermembrane space, with the matrix becoming negatively charged with the departure of H⁺ (N side, negative), and the intermembrane space becoming positively charged (P side, positive). For instance, complex I catalyzes two simultaneous and obligatory pro-
cesses: the exergonic transfer of one hydrogen atom and one electron from NADH and of a \(\text{H}^+\) from the matrix to ubiquinone, coupled to the endergonic transfer of 4 \(\text{H}^+\) from the matrix to the intermembrane space (155).

The chemical free energy of the fall in redox potential of the electrons passing through the respiratory complexes is used to generate a \(\text{H}^+\) electrochemical potential gradient, \(\Delta \Psi_m\), expressed in electric potential units as the proton-motive force \((\Delta p)\) (106) as \(\Delta p = \Delta \Psi_m - (2.3 \text{ RT}/F) \Delta \phi\), that at 37°C, results: \(\Delta p = \Delta \Psi_m - 60 \Delta \phi\). In the equation, \(\Delta \Psi_m\) is the electric potential across the inner mitochondrial membrane, \(\Delta \phi\) is the pH gradient across the inner membrane, and \(\text{R}, \text{T}, \text{and F}\) refer to the gas constant, the absolute temperature, and the Faraday constant, respectively. Under most conditions, \(\Delta \Psi_m\) is the dominant component of \(\Delta p\), accounting for 150–180 mV of a \(\Delta p\) of 200–220 mV (107). The \(\Delta p\) drives ADP phosphorylation and stops electron flow in the controlled metabolic condition of absence of ADP. In the biophysical basis of respiratory control, \(\Delta p\) is able to stop exergonic substrate oxidation by a free energy equilibrium between electron flow between redox pairs and \(\text{H}^+\) flow between compartments. Moreover, membrane potential provides the driving force for cation, such as \(\text{K}^+\) and \(\text{Ca}^{2+}\), uptake by mitochondria.

**Electrochemical Potential and F1-ATPase Molecular Rotor are used to Phosphorylate ADP**

The whole process of oxidative phosphorylation depends critically on the integrity and impermeability of the inner mitochondrial membrane. The first part of the process converts the chemical potential of NADH and succinate oxidation into a \(\text{H}^+\) electrochemical gradient, and the second part of the process, catalyzed by the ATP synthase uses the \(\text{H}^+\) electrochemical gradient to drive the endergonic ATP synthesis. The process is thermodynamically possible because electron transfer releases and the proton-motive force conserves enough free energy, about 34 kJ per mol of electron pair, to drive the formation of one mol of ATP, which requires \(~32\) kJ.

Mitochondrial ATP synthase (complex V) is a F-type ATPase that has two distinct components: \(\text{F}_1\), a peripheral membrane protein, and \(\text{F}_0\), which is integral to the membrane (18, 130, 156). The \(\text{F}_1\) catalytic domain is a globular assembly of 5 proteins \(\alpha, \beta, \gamma, \delta, \text{and} \epsilon\) with the stoichiometry 3:3:1:1:1. The \(\gamma, \delta, \text{and} \epsilon\)-subunits form a central stalk linking the \((\alpha\beta)_3\) subcomplex of the \(\text{F}_1\) domain to \(\text{F}_0\). The \((\alpha\beta)_3\) subcomplex and the \(\text{F}_0\) domain are linked by a peripheral stalk. The \(\gamma\)-subunit protrudes from \((\alpha\beta)_3\) subcomplex and the \(\delta\)- and \(\epsilon\)-subunits are associated with its foot. The movement of the subunits of ATP synthase is critical to its function, with the central stalk rotating at 50–100 times/s. The rotation is produced in \(\text{F}_0\), which is in contact with the foot of the central stalk and is fuelled by the \(\text{H}^+\) flow (156).

The rate of mitochondrial respiration depends on ADP availability to \(\text{F}_1\)-ATP synthase. The gradients of ADP and ATP across the inner membrane are equilibrated by the adenine nucleotide translocase activity, which is functional to provide ADP to the matrix and ATP for energy-dependent processes to the cytosol.

The experimental value for the \(\text{H}^+\) required to drive the synthesis of one ATP molecule is \(~3–4\) (30, 106). The phosphorylation efficiency is determined in isolated coupled mitochondria as the ADP/O ratio, with experimental values of 2.6–2.7 for NAD-dependent substrates and 1.6–1.7 for succinate oxidation. These values are close to the theoretical ADP/O ratios of 2.5 and 1.5, respectively, considering that the \(\text{H}^+\) pumped out per pair of electron are 10 for NADH and 6 for succinate.

**Mitochondrial \(\text{Ca}^{2+}\) Sequestration**

When mitochondria are supplemented with \(\text{Ca}^{2+}\), even in the presence of ADP, \(\text{Ca}^{2+}\) ions are internalized into mitochondria in an energy-dependent process and ATP synthesis is abolished. Mitochondria take up \(\text{Ca}^{2+}\) in exchange for \(\text{H}^+\) by an ATP-powered or membrane potential driven \(\text{Ca}^{2+}/\text{H}^+\) pump with a stoichiometry of 1:1. The stimulation of respiration by 2 \(\text{Ca}^{2+}\) ions yield the same amount of extra \(\text{O}_2\) uptake as one molecule of ADP (26). Mitochondria accumulate large amounts of \(\text{Ca}^{2+}\) with simultaneous uptake of \(\text{P}_i\) and precipitation in the matrix of an insoluble salt similar to hydroxylapatite, in a way that the ionic \(\text{Ca}^{2+}\) concentration in the matrix is only moderately altered (26). Another route of \(\text{Ca}^{2+}\) uptake is functionally related with the opening of the \(\text{Ca}^{2+}\)-mediated permeability pore (136), a sudden increase in inner membrane permeability induced by a large series of compounds that collapses membrane potential and permits the efflux and influx of large molecules and ions. Intramitochondial \(\text{Ca}^{2+}\) is recognized as an allosteric activator of matrix dehydrogenases, such as NAD+-isocitrate dehydrogenase, pyruvate dehydrogenase and \(\alpha\)-ketoglutarate dehydrogenase (104) and as co-factor of mitochondrial nitric oxide (NO) synthase (mtNOS) (59).

**REGULATION OF MITOCHONDRIAL RESPIRATION**

It is now known that mitochondrial oxidative phosphorylation is regulated by three metabolites: ADP, \(\text{O}_2\), and NO. As early recognized, the rate of respiration and of ATP synthesis are determined by cellular energy needs, which are expressed as cytosolic ADP concentration or as phosphorylation potential \((\text{[ATP]/[ADP][P_i]}\)), in which the operational part is the \([\text{ATP}]/[\text{ADP}]\) ratio. When the cellular demand for energy increases, ATP breakdown to ADP and \(\text{P}_i\) increases and lowers the phosphorylation potential. With more ADP available, the rate of respiration increases, causing regeneration of ATP. Usually, the phosphorylation potential is finely regulated and fluctuates only slightly in most tissues. Chance and Williams (32) defined the operational concepts of mitochondrial metabolic states and respiratory control. State 4, with availability of respiratory substrate but not of ADP, was described as “controlled or resting respiration”, whereas state 3, with ample respiratory substrate and ADP availability, was defined as the “active respiration”, i.e., the maximal physiological rate of ATP production and \(\text{O}_2\) consumption. The rates of respiration of isolated mitochondria are 5 to 8 times faster in state 3 than in state 4, i.e., the respiratory controls are 5 to 8. Considering the rates of mitochondrial \(\text{O}_2\) uptake in both states 4 and 3, and of \(\text{O}_2\) uptake of perfused organs, it was estimated that mammalian mitochondria under physiological conditions are mostly (60–70%) in state 4, whereas the rest (30–40%) are in state 3 (15). This means that in a physiological setting there is only a 30–40% utilization of the ATP-producing capacity. The linear rates of \(\text{O}_2\) uptake shown by tissue slices and perfused organs...
are interpreted as a fast switching of mitochondria between metabolic states 3 and 4. NO is a physiological regulator of mitochondrial respiration. In the arterioles, NO produces vasodilatation and increases blood flow and O2 delivery to the tissues IV (37). However, in mitochondria NO inhibits respiration, by a rapid, selective, potent, and reversible inhibition of complex IV (21, 27, 35, 128). The inhibition occurs in competition with O2, so that NO dramatically increases the O2 concentration that yield half-maximal rate of O2 uptake (2), from 1.4 μM O2 in the absence of NO to 3.4 μM O2 in the presence of 0.2 μM NO (16).

In mitochondria, synaptosomes and mitochondrial membranes half-inhibition of respiration occurs at O2/NO ratios of 150 (2) to 600 (21). Macrophages, astrocytes, and endothelial cells under inflammatory conditions and with increased iNOS expression produce sufficient NO to inhibit their own respiration and also the O2 uptake of surrounding cells (99).

**GENERATION OF MITOCHONDRIAL FREE RADICALS**

Mitochondria isolated from liver and heart were described by Boveris and Chance in 1972–1973 as an active source of H2O2 that diffuses to the cytosol (14, 17). Shortly after, O2- was recognized as the stoichiometric precursor of mitochondrial H2O2 and ubisemiquinone (UQH2-) was indicated as the main source of O2- upon autooxidation (13, 25, 47). Mitochondria are considered the main quantitative source of O2- and H2O2 in mammalian organs (31). However, there is a standing criticism by Nohl and colleagues that mitochondria in vivo are not an effective source of O2- and H2O2 and that the determined rates are artifactual (121).

A few years ago, mitochondria were also recognized as a source of NO by two independent research groups, Ghafourifar and Richter (58) and Giulivi et al. (62). Mitochondrial NO is referred as involved in the molecular mechanism of neurological diseases.

**Mitochondrial production of O2- and H2O2**

The majority of mitochondrial O2-, 70–80%, is vекторially released to the mitochondrial matrix and 20–30% is released into the intermembrane space. Two main O2- generating reactions have been described by auto-oxidation of intermediate semiquinones: UQH2- for the ubiquinol/ubiquinone redox pair (UQH2- + O2 = UQ + H+ + O2-) (13) and the FMN- of the FMNHH2/FMN coenzyme of NADH dehydrogenase (FMNHH2 + O2 = FMN + H+ + O2-) (150). The semiquinones are collisionally and nonenzymatically oxidized by molecular O2 to yield O2-. Ubisemiquinone is the quantitative main source of univalent O2- reduction to yield O2 (129, 150). A role of the Fe-S cluster N1a of complex I has been reported in preventing O2- generation (74).

The mitochondrial production of H2O2 is modulated by the mitochondrial metabolic state and by the intramitochondrial concentration of NO. The production of H2O2 in state 4 is ~4 to 5 times higher than in state 3: 0.3–0.8 nmol H2O2·min−1·mg protein−1 for state 4 and 0.05–0.15 nmol H2O2·min−1·mg protein−1 for state 3 (12). Ion movements through the inner membrane strongly affect the rates of H2O2 production, indicating a membrane potential regulation of the auto-oxidation of UQH2- (24). In the rat heart and liver, mitochondrial H2O2 production accounts for ~0.5% of the physiological organ O2 uptake with succinate or malate-glutamate as substrate (12) and for ~0.15% with palmitoyl carnitine as substrate (148).

**Mitochondrial Production of NO**

NO is synthesized by the NOS enzymatic reaction that requires arginine, NADPH2 and O2 as substrates and that produces citrulline, H2O2, and NO (NADPH2 + Arg + O2 = NADP + H2O + Cit + NO). Three different genomic NOS are known: neuronal NOS (nNOS or NOS-1); inducible or macrophage NOS (iNOS or NOS-2) and endothelial NOS (eNOS or NOS-3). The mtNOS has been identified as the splice variant α of the nNOS with the posttranslational modifications of myristilation and phosphorylation (49, 55). The intramitochondrial concentrations of NADPH2, arginine, O2, and Ca2+ are in excess or in the range needed for enzymatic activity (152). Mitochondria and submitochondrial preparations yield rates of 0.25–0.90 nmol NO·min−1·mg protein−1. However, there is still some controversy concerning the existence of mtNOS (20).

The intramitochondrial steady-state concentrations of NO are calculated as 50–200 nM NO (129) and a release of 29 nM NO was electrochemically measured after supplementation of a single mitochondrion with Ca2+ (80). Under physiological conditions tissues are oxygenated at ~25 μM O2 and mitochondria are exposed, by the NO generated by mtNOS, to [O2]/[NO] ratios of ~150–300, which inhibit cytochrome oxidase by 50–25% (2, 16).

NO, produced by NO donors or by mtNOS, inhibits complex III electron transfer (half inhibition of electron transfer between cytochromes b and c occurs at 0.2–0.4 μM NO) and increases O2- and H2O2 production in submitochondrial particles and in mitochondria (128). The reaction is frequently referred as involved in the molecular mechanism of neurological diseases.

**Intramitochondrial metabolism of O2-, H2O2, and NO and diffusion of NO and H2O2 out of mitochondria**

The intramitochondrial metabolites O2-, H2O2, NO, and ONOO- are pro-oxidants potentially leading to oxidative stress and damage and are nowadays considered as the chemical species that afford the molecular mechanism of tissue dysfunction in inflammation, neurological diseases, and aging. Two of them, O2- and NO, are free radicals; however, they are unreactive and sluggish and do not participate in propagation reactions and only show termination reactions yielding H2O2 and ONOO-. The latter two species are potentially harmful after homolytic scission due to the generation of the reactive hydroxyl radical. In the case of ONOO-, the homolytic scission also yields the free radical NO2-, which is involved in protein nitration (12, 132).

The main part of mitochondrial O2- is released into the matrix where it encounters specific intramitochondrial manganese superoxide dismutase (MnSOD) that catalyzes the reaction: 2 O2- + 2 H+ = O2 + H2O2. Steady-state concentrations of 0.2–0.3 nM O2- were estimated for the mitochondrial matrix, with a content of 10–40 μM MnSOD reaction centers (12). The O2- released in the intermembrane space (69) reacts with cytochrome c, located on the P side of the inner
membrane, and with the Cu,Zn-SOD of the intermembrane space (123).

Glutathione peroxidase catalyzes H$_2$O$_2$ and ROOH reduction by GSH [H$_2$O$_2$ (ROOH) + 2 GSH $\rightarrow$ GSSG + 2 H$_2$O (ROH + H$_2$O)] and is the unique enzyme that uses H$_2$O$_2$ in the mitochondria of most mammalian organs (31), the exception being heart, where a mitochondrial catalase has been described (133). Mitochondrial glutathione peroxidase activity accounts for ~60% of the rate of H$_2$O$_2$ production and indicates both a role of H$_2$O$_2$ as messenger and a function of glutathione peroxidase in the reduction of mitochondrial hydroperoxides. Glutathione deficiency is associated with widespread mitochondrial dysfunction leading to cell damage (105). Glutathione peroxidase requires a continuous supply of GSH, since the co-factor becomes oxidized by H$_2$O$_2$ or hydroperoxide. A separate enzyme, NADPH$_2$-dependent glutathione reductase, is located in the mitochondrial matrix and shows a high activity that keeps the GSH/GSSG couple in a highly reduced state (31). Boveris and co-workers (152) reported that mitochondria isolated from rat heart, liver, kidney, and brain release NO and H$_2$O$_2$ with rates that are higher in state 4 than in state 3. NO release from rat liver mitochondria shows an exponential dependence on membrane potential (152), as reported for mitochondrial H$_2$O$_2$ production by Korshunov et al. (84). The data support the speculation that NO and H$_2$O$_2$ diffusion to the cytosol reflect a high mitochondrial energy charge and signal such metabolic situation to the cytosol promoting mitochondrial biogenesis.

NO and O$_2$ metabolism in the mitochondrial matrix are linked by the very fast, diffusion limited, reaction between NO and O$_2$ to produce peroxynitrite (NO + O$_2$ $\rightarrow$ ONOO$^-$) (4, 83). This oxidative utilization of NO is the main (80%) pathway of NO metabolism but only a minor part (15%) of O$_2$ utilization, whereas the reductive utilization of NO by ubiquinol and cytochrome oxidase provides minor (20%) pathways of NO catabolism (129).

Peroxynitrite is a powerful oxidant that, as a charged species, is badly diffusible from the intramitochondrial space. Peroxynitrite inhibits both complex I and III (36, 135); the effects are irreversible and are usually observed in situations in which sustained high levels of ONOO$^-$ lead to mitochondrial dysfunction and apoptosis. A level of 2–5 nM ONOO$^-$ has been estimated for the mitochondrial matrix under physiological conditions (129, 151), and levels above 20–30 nM are considered cytotoxic. The existence of a stable low ONOO$^-$ concentration is indicated by the detection of nitrotyrosine in normal mitochondria. At high levels, ONOO$^-$ oxidizes and nitrates lipids and proteins and impairs mitochondrial function. The whole syndrome of mitochondrial dysfunction appears driven by excess NO and ONOO$^-$ as postulated for ischemia-reperfusion, inflammation, and aging (5, 63).

There are effective reductants for matrix ONOO$^-$ due to their reaction constants and concentrations. In rat liver, 3.8 mM NADH$_2$, 2.6 mM UQH$_2$, and 3.0 mM GSH in the mitochondrial matrix account for 33, 46, and 21% of the matrix capacity to reduce ONOO$^-$ (151). Peroxinitrite readily reacts with CO$_2$ to yield the adduct ONOOCO$_2^-$ ($k = 6 \times 10^4$ M$^{-1}$s$^{-1}$) (11) that also participates in oxidation and nitration reactions. Formation of the adduct decreases the steady-state level of ONOO$^-$ from 30 nM to 2 nM (151) and is considered a detoxification pathway for mitochondrial ONOO$^-$ that takes advantage of the high mitochondrial CO$_2$ concentration (1 mM) (132). Finally, NO has been found an effective chain-breaker antioxidant by termination reactions with the free radical intermediates of lipid peroxidation (137).

**EFFECTS OF AGING ON MITOCHONDRIAL ENERGY TRANSDUCTION**

Mitochondria were brought to attention in aging biology due to 1) the central role of mitochondria in producing chemical energy (ATP) to meet cellular requirements, and 2) the declines of basal metabolic rate and of physical performance in energy-requiring tasks, which are characteristic of the aging process (103).

An age-dependent impairment of mitochondrial function may comprise: 1) decreased electron transfer rates, 2) increased H$^+$ permeability of the inner membrane, and 3) impairment of the H$^+$-driven ATP synthesis.

**Decreased Electron Transfer in Aging**

A widely recognized experimental fact concerning aging and energy transduction is that a decreased electron transfer activity is observed in mitochondrial membranes and mitochondria isolated from rat and mice tissues upon aging. Complexes I and IV show a selectively decreased enzymatic activity in mitochondria isolated from rat and mice liver, brain, heart, and kidney upon aging, whereas complexes II and III are largely unaffected (7, 87, 93, 101, 110, 112–115, 161). The decreased activity of complex I is determined in mitochondrial fragments as a decreased NADH-cytochrome c reductase activity with a simultaneously unchanged succinate-cytochrome c reductase activity (115) or as decreased NADH-ubiquinone reductase activity (93), and in coupled mitochondria as a decreased respiratory rate in state 3 with malate-glutamate, or other NAD-dependent substrates with a simultaneous unchanged respiratory rate with succinate as substrate (114) (Fig. 1). In our experience, direct assay of complex I using artificial quinone electron acceptors that exhibit relatively slow rates of electron transfer, may underestimate enzyme activity and miss the impairment in complex I function. Lenaz et al. (93) reported decreased complex I activity in aging and proposed a procedure to calculate complex I activity from aerobic NADH oxidation.

The decreased activity of complex IV is usually determined by the enzymatic assay in mitochondrial fragments (115). Figure 1 illustrates the determination of the enzymatic activity of mitochondrial electron transfer complexes.

The histochemical determinations of NADH-dehydrogenase in rat kidney (111), and of cytochrome oxidase in human substantia nigra (76), rat hippocampal dentate gyrus (8), and monkey tissues (109) show decreased activities upon aging.

The decreased enzymatic activities of complexes I and IV could be a consequence either of an enzyme inhibition by aging-produced inhibitors, or of aging-mediated enzyme modification, or of decreased protein expression. Western blot analysis showed that aging is associated with a selectively decreased content of complexes I, II, and IV in human skeletal muscle, whereas complex III was not altered (10). In the same line, aging did not alter the content of catalytic centers of complex III (cytochromes b and c$_1$ and [Fe-S] protein) in heart.
interfibrillar mitochondria (94). The content of ubiquinone was reported decreased in the skeletal muscle of old mice (90).

Northern blot analysis of the respiratory complexes in mice brain mitochondria revealed an increased expression of mitochondrial-encoded genes in complexes I, III, IV, and V in 12- and 18-mo-old mice compared with 2-mo-old mice, suggesting a compensatory mechanism of overproduction of electron transfer proteins. However, the mRNA expression of all genes was decreased in 24-mo-old mice, suggesting that compensation by gene upregulation cannot be sustained for a long time and that downregulation of expression shows up in the late stage of aging (98).

Mitochondrial respiration can be limited by the activities of the NAD-dependent dehydrogenases. There is no clear evidence if the activities of the dehydrogenases of the citric acid cycle are modified during aging. In mitochondria isolated from kidneys of old mice, aconitase activity exhibited a significant decrease with age (160), whereas α-ketoglutarate dehydrogenase exhibited a modest decrease and NADP⁺-isocitrate dehydrogenase activity increased moderately. The activities of citrate synthase, NAD⁺-isocitrate dehydrogenase, succinyl-CoA synthetase, succinate dehydrogenase, fumarase, and malate dehydrogenase were not affected. The ratio of the intramitochondrial redox indicator, NADPH₂/NADP, was higher in young compared with old animals, while the NADH₂/NAD ratio remained unchanged (160). In another study, the activities of citric acid cycle enzymes of heart and skeletal muscle mitochondria, such as isocitrate dehydrogenase, α-ketoglutarate dehydrogenase, succinate dehydrogenase, and malate dehydrogenase, were found decreased in aged rats (87).

Acyl carnitine transferase, that catalyzes fatty acid transport to the mitochondrial matrix, is essential for mitochondrial function and has been reported selectively decreased in aging (96). The proteomic analysis of aged male *Macaca fascicularis*...
Increased \( H^+ \) Permeability of the Inner Membrane

There are speculations about an increased \( H^+ \) permeability of the inner mitochondrial membrane and a consequent failure in maintaining the \( H^+ \) electrochemical gradient in aging. However, there is no reported evidence of an increased \( H^+ \) permeability in old animals. Indirect evidence from decreased membrane potential in astrocytes from old animals is consistent with an impairment of the \( H^+ \) impermeability of the inner membrane (95). Brain mitochondria isolated from aged rats had a larger volume and increased water permeability when challenged by a hypotonic medium, but liver mitochondria did not show such difference between young and old animals (112). Liver mitochondria from old rats showed decreased membrane potential, an impairment that was improved by treatment with an antioxidant extract (139). Cortical and striatal mitochondria of aged rats showed lower membrane potentials with increased susceptibility to the permeability transition at advanced ages (88). Mitochondria isolated from thoraces of \textit{Drosophila melanogaster}, mainly flight muscle mitochondria, showed a significant decrease in state 3 respiration, respiratory control ratios, and uncoupled respiration rates, as a function of age, using either NAD- or FAD-linked substrates, but there were no differences in state 4 respiration rates, which does not indicate increased \( H^+ \) permeability in aging (51).

Conservation of the \( H^+ \)-Driven ATP Synthesis in Aging

The \( H^+ \)-driven ATP synthesis in aging has been estimated from the determination of the ADP/O ratios in coupled mitochondria. There is no report on the effect of aging on the biochemical activity of the ATP synthase complex or on F1-ATPase activity. Two studies reported slightly depressed and not affected ADP/O ratios in aged brain (114) and liver (110, 114) mitochondria. In both cases, the almost no effect on the ADP/O ratios was simultaneous to a decreased state 3 respiration rate, which indicated an impairment of electron transfer.

The activity of adenine nucleotide translocase, that catalyzes the fast ADP/ATP exchange between cytosol and mitochondria, was reported decreased in aging (159).

FREE RADICALS, OXIDATIVE DAMAGE, MITOCHONDRIAL DYWFUCTION AND APOPTOSIS

The free radical theory of aging is based in the works of Gerschman (57) and Harman (70), and when focused in mitochondria emerged as the mitochondrial hypothesis of aging (5, 71, 154). Mitochondria are considered the pacemakers of tissue aging due to the continuous production of free radicals, oxygen, and nitrogen free radicals and reactive species, and to the selective oxidative damage that leads to mitochondrial dysfunction. Gerschman postulated in 1954 that oxygen free radicals were the common biochemical mechanism of \( O_2 \) and radiation toxicity after finding synergism between radiation and hyperbaric \( O_2 \) in decreasing the survival of exposed mice (57).

Oxidative Damage and Mitochondrial Dysfunction

Dysfunctional mitochondria are characterized by decreased state 3 respiration, respiratory controls, and membrane potential, and increased rates of state 4 respiration and mitochondrial size and fragility associated to an increased content of oxidation products. Dysfunctional mitochondria are observed in aging, and also in pathological situations as ischemia-reperfusion and inflammation (5, 63, 112, 114).

The experimental determination of increases in oxidation products that correspond to the free-radical mediated oxidation of mitochondrial constituents, such as phospholipids, proteins and DNA, constitutes the usual finding in aging studies. Phospholipid oxidation products, as TBARS (112–115) and ROOH (139, 145), protein oxidation products, as protein carbonyls (54, 112–114, 149), DNA oxidation products, as 8-HO-DG (5, 138) were found increased in aged animals. Protein oxidation and nitration appear to have capital importance in the molecular mechanisms involved in cell turnover and cell cycle and in triggering apoptosis. Oxidized and nitrated proteins appear as the sand grains of the sand clock that determines cell life. The proteolytic enzymes that degrade modified proteins decline with aging which implies a less efficient removal and an accumulation of oxidized proteins (22, 66). Kozlov et al. (85) identified skeletal muscle, heart and lung as the main sources of oxygen radicals in vivo in old rats by injection of a spin trap. The spin trap reacts with \( O_2^- \) and with ONOO− and provides conclusive evidence of the generation of these species under physiological conditions.

Proteomic techniques used with rat heart homogenate and mitochondria showed protein nitration in aging. A total of 48 nitrated proteins was identified; among them were \( \alpha \)-enalase, \( \alpha \)-aldolase, desmin, aconitate hydratase, methylmalonate semialdehyde dehydrogenase, 3-ketoacyl-CoA thiolase, acetyl-CoA acetyltransferase, malate dehydrogenase, glyceraldehyde 3-phosphate dehydrogenase, creatine kinase, electron-transfer complex I flavoprotein, MnSOD, F1-ATPase, and the voltage-dependent anion channel (81). The MnSOD activity in mice brain mitochondria decreased linearly upon aging from 28 to 76 wk of age, up to 67% (114).

Aging is characterized by a general decline of physiological performances with a more marked effect in the functions that depend on the central nervous system. In a mechanistic approach, the decreases in neuromuscular coordination and maze performance in mice upon aging were found directly related to the brain content of lipid and protein oxidation products (54, 113–115).

Mitochondrial inner membrane enzymes that are markers of aging

Accumulation of oxidative damage and decrease of mitochondrial energetic competence to produce ATP in the organs and tissues of aged mammals are two underlying concepts of the mitochondrial hypothesis of aging. Concerning the decreased capacity to produce ATP, a reduction of the mitochondrial mass in brain and liver as well as the phosphorylating capacity of the ATP synthase were ruled out (112, 114) and decreased rates of electron transfer were identified as the
mechanism of mitochondrial dysfunction in aging (112–115). Accordingly, the activities of mitochondrial complexes I and IV were found decreased upon aging. A 17–33% decrease of NADH-cytochrome c reductase activity (complexes I + III) at 52–76 wk of mice age, is interpreted as complex I decreased activity, since succinate cytochrome c reductase activity (complex I + II) was not affected by aging (113–115). Cytochrome oxidase activity was also decreased by 24–36% at the same time points (113–115). Thus the activities of both complex I and complex IV were decreased by about one-third in senescent mice and are considered effective markers of aging. Moreover, brain mitochondrial enzyme activities keep a quantitative relationship and correlate significantly with survival (Fig. 2).

Oxidative damage, as determined by the mitochondrial content of protein carbonyls and TBARS, correlated negatively with the activities of complex I and complex IV. The observation supports the view that oxidatively modified proteins and the increased level of lipid peroxidation products are part of the molecular mechanism of the decreased enzymatic activity (113–115). Moreover, it is likely that the inhibition of complex I activity upon aging occurs with increased reduction of complex I, i.e., higher levels of FMNH₂ and FMNH⁺, which lead to an increased rate of O₂⁻ generation (Fig. 3).

Interestingly, mice neurological function, as determined by the tightrope test to evaluate neuromuscular coordination and by the T-maze test to evaluate memory and exploratory capacity, was linearly related to brain complex I and IV enzymatic activities (113, 114) and negatively correlated with the mitochondrial content of brain lipid and protein oxidation products (54, 113, 115) (Fig. 4). Applying the concept of rate limiting step in complex systems, it follows that decreased rates of electron transfer and a limiting energy supply by brain mitochondria are factors in the neurological dysfunction inherent to physiological aging.

The activity of mtNOS, an integral inner mitochondrial membrane enzyme, decreased significantly (40–65%) in the brain and liver of senescent mice and old rats (112, 114). The magnitude of this change makes mtNOS the most sensitive marker of aging, more sensitive than the already considered complexes I and IV. The decreased activity of mtNOS suggests a loss in critical regulatory roles of mitochondrial NO in aging (114). The association between mtNOS activity and cellular homeostasis has been called the pleiotropic effect of mtNOS and was originally used to describe preserved kidney and heart functions (161).

Recently, NO has been implicated in mitochondrial biogenesis by the stimulation of guanylate cyclase, generation of cGMP and activation of PGC1-α (120). It was claimed that the pleiotropic effect occurs through NO and H₂O₂ diffusion from mitochondria to the cytosol, a signal that indicates a high mitochondrial energy charge (117). MtNO production seems to be the main signal for the cell changes in the ovarian cycle (117) and to provide the 70% of cellular NO in the heart (161). The general role of mitochondria as ATP provider, as source of NO to signal for mitochondrial proliferation and for mitochondria-dependent apoptosis, and as the main intracellular source of O₂⁻ and H₂O₂ (31) appears well adapted to serve the proliferation-apoptosis sequence of the ovarian cycle (117). Thus, the marked decrease in mtNOS activity in aged brain mitochondria is interpreted as a decrease in mitochondrial signaling that hinders a sustained neuronal homeostasis in aging (114).

In summary, the inner membrane mitochondrial enzymes mtNOS, complex I, and complex IV are markers of tissue aging (Fig. 2).

Mitochondria-dependent cell death program

The pivotal role of mitochondria in the execution of cell death is well established (86). The sequence of biochemical and cellular events in mitochondria-dependent apoptosis has been reported by Bustamante et al. (23) in thymocytes, describing the time course and the quantitative consideration of the signals and the involved molecular markers. At the initial phase (2.5–30 min), cytosolic [Ca²⁺] and [NO] exerted their signaling by marked (7–8 times) changes in their levels (23). The first intracellular signal was the increased cytosolic [Ca²⁺] which occurred in a 2–3 min and is due to inhibition of endoplasmic reticulum Ca²⁺-ATPase and to depletion of intrareticular Ca²⁺ stores (78). The next rapid observed effects, with a estimated half-life (t½) of ~15 min, were the parallel increases in mitochondrial NO production and in cellular H₂O₂ steady-state concentration (23). As said, the rate of mitochondrial H₂O₂ production is directly regulated by mtNOS activity,
since the enzyme product NO augments the rate of \( \text{O}_2^- \) production by inhibition of electron transfer at complex III (128). Increased intracellular \( \text{Ca}^{2+} \) is associated with the activation of the whole NOS family (34) and with cell death.

The increased levels of NO, \( \text{O}_2^- \), and \( \text{H}_2\text{O}_2 \) constitute the molecular mechanism for the increased free radical-dependent lipid peroxidation process, with increases in cellular ROOH and TBARS production and with \( t_{1/2} \) of 27–30 min in thymocytes. Thymocyte mitochondria were able to stand up cellular oxidative stress and remained functional for \( \sim 1 \) h, as an indication of the resistance of these organelles to oxidants. At the intermediate phase (30–130 min) in which apoptosis is still reversible, the molecular contribution or signaling by \( \text{H}_2\text{O}_2 \) and ROOH occurs with their intracellular levels increased by a factor of \( \sim 2 \) (23).

Mitochondrial dysfunction followed, with a \( t_{1/2} \) of 101–133 min in thymocytes, as described by the abolition of respiratory control, inner membrane depolarization, and cytochrome c release (23). Increased intramitochondrial steady-state levels of NO and \( \text{O}_2^- \) lead to increased rates of formation and steady-state levels of ONOO\(^-\) with further inhibition of complex III (27, 128) and inactivation of complex I (36, 135). The molecular markers of the final and irreversible phase of apoptosis, such as caspases-3 activity and DNA fragmentation, were again markedly increased, by a factor of 4, in agreement with the irreversibility of the process at that point (23).

Tissues, such as brain and specific brain areas, as the hippocampus, that have a slow turnover of mitochondria and mitochondrial components, show a cellular accumulation of dysfunctional mitochondria with increased apoptosis upon aging, a condition that drives the tissue to a physiological deficit (64).

**PHYSIOLOGY OF THE DECREASED CAPACITY OF ENERGY SUPPLY**

Reduction of the capacity to produce ATP in the organs and tissues of old mammals is one of the basic concepts of the mitochondrial hypothesis of aging. The experimental evidence, as mentioned in section 5.2, points out to a selectively decreased rate of electron transfer as the molecular mechanism of the mitochondrial impairment associated with aging.

The \( \sim 35\% \) decreased activity of complex I in brain and liver of old rats is close to the limit of a tolerable functional damage in terms of basal energy production. In rat liver, ATP is provided by the respiration of about 36% of the mitochondrial mass in metabolic state 3 (15). Under conditions of increased ATP demand, liver mitochondria will be able to increase ATP synthesis up to 2.8 times by switching more mitochondria from the resting state 4 to the active state 3. Aged hepatocytes, with a 30% reduction in complex I activity, will be able to increase ATP production only up to 1.9 times by switching mitochondria from state 4 to state 3. The situation is clearly worst in the brain due to the lower mitochondrial mass and where aged neurons are close to be unable to respond to any increased ATP demands (112).
The observed age-dependent decrease in marker activities in brain mitochondria that in senescent animals reaches 35–65% is simultaneous with the existence of a mitochondrial subpopulation with increased size (139) and fragility (112). Most neurons are long living cells, with a slow turnover of mitochondria and of mitochondrial components, that age at the same time as the animal ages with neurogenesis spatially restricted and quantitatively negligible (64).

Liver mitochondria isolated from young and old animals did not exhibit a significant difference in fragility (112). In hepatocytes, mitochondria are continuously subjected to protein and phospholipid turnover and to elimination of dysfunctional organelles. The cellular population of damaged mitochondria is likely to become determinant in the signaling for apoptosis as hepatocytes reach their life span limit. A fifths of mitochondrial proteins and mitochondrial fractions gives 7–10 days for liver mitochondria and 4–6 wk for brain mitochondria (64). The slower turnover of brain mitochondria makes possible the detection of a fraction of dysfunctional mitochondria with impaired electron transfer and increased fragility, which may correspond to subpopulations of enlarged mitochondria in morphological or flow cytometry studies.

Considering the evolution of the knowledge on brain aging and the complexity and variety of metabolic conditions in brain nuclei and areas, it is nowadays necessary to attempt the determination of mitochondrial function in mitochondria isolated from brain nuclei, as hippocampus, that are specially sensitive to aging. Preliminary results in our laboratory show a selective mitochondrial damage, similar to the one described here for whole brain, in the hippocampus of aging rats.

CONDITIONS THAT IMPROVE SURVIVAL AND MITOCHONDRIAL FUNCTION

Some conditions that are able to increase survival and to improve the neurological deficits of mice senescence have been found to also decrease the age-related oxidative damage and dysfunction of brain mitochondria. The age-related oxidative damage is, in a first approximation, due to an increased rate of generation of oxidants. The hypothesis of a decrease in the activity of the antioxidant enzymes, in spite of numerous studies that measured age-related changes in antioxidants defenses, failed to produce a clear evidence of decreased antioxidant enzymes in mice and rats in aging (5). However, the interspecies comparisons of oxidative damage, antioxidant content and oxidant generation provide some of the most compelling evidence that oxidants are significant determinants of life span (43).

The selected life conditions that were able to improve survival in mice are similar to recommendations that are commonly followed by many aging humans, i.e., antioxidant supplementation, caloric restriction, high spontaneous neurological activity, and moderate physical exercise. There is evidence that these conditions increase mice survival associated with improved brain mitochondrial function (113–115). However, most of the studies show a clear increase in median lifespan without a significant modification in maximal lifespan. The kinetics of aging are described by the survival curves (Fig. 5) which shows mice survival curves with increased either median or maximal life span in modified life conditions.

![Fig. 5. Survival curves of Swiss CD1-UCadiz male mice subjected to selected life conditions. Control mice (n = 50): median lifespan, 61 ± 4 wk; maximal lifespan, 116 ± 4 wk. Moderate physical exercise (n = 40): median lifespan, 80 ± 4 wk; maximal lifespan, 109 ± 4 wk. Vitamin E-supplemented mice (n = 40): median lifespan, 85 ± 4 wk; maximal lifespan, 136 ± 4 wk.](http://ajpcell.physiology.org/)

**Antioxidant Supplementation**

Mice of the strain CD-1/UCadiz chronically supplemented with high doses of vitamin E (5.0 g dl-RRR-α-tocopherol acetate/kg of food) showed increased survival, with a 40% increased median life span and a 17% increased maximal life span (Fig. 5) (114). The strain CD-1/UCadiz has similar survival to AKR, SAM, NZB/Lac and SJL/J that are senescence accelerated strains and that are used as models of aging, considering that the whole aging process is similar to normal mice and that can be extrapolated to primates (53). Vitamin E also retarded the neurological deficits associated with aging, since mice that received vitamin E exhibited better performances in behavioral tests. Moreover, both the increase in mitochondrial oxidative damage, and the diminished rates of electron transfer in brain mitochondria of aged and senescent mice were ameliorated by vitamin E supplementation (Table 1) (114). The effects of aging and vitamin E on mitochondrial O2 uptake and oxidative phosphorylation were determined in mice brain and liver after 24 wk of vitamin E supplementation. The rate of respiration of brain mitochondria in active state 3 was 24% decreased in 52 wk mice, an effect that was 50% prevented by vitamin E supplementation. Respiratory control and ADP/O ratios were neither affected by aging nor by vitamin E supplementation (114). The functional activity of mtNOS in the regulation of state 3 O2 uptake was decreased ~50% by aging and the loss was about 64% prevented by vitamin E, in clear agreement with the effects observed in mtNOS biochemical activity (Table 1) (114). The effects of aging and vitamin E supplementation on liver mitochondria, considering respiration, oxidative phosphorylation and mtNOS functional activity, were qualitatively similar to the ones observed in brain mitochondria, but less marked (114).

Dietary supplementation with acetyl-carnitine and lipoid acid (68, 96) and with a flavonoid-rich vegetable extract (9) produce a prevention of the age-associated decline in mouse physiological functions and interpreted as due to protection or remediation of an oxidative damage in mitochondria.
The addition to the diet of low molecular weight antioxidants, such as 2-mercaptoethylamine (71), ethoxiquin (40) and 2-ethyl-6-methyl-3-hydroxy-pyridine (50), was able to produce a 13–29% increase in median life span.

Other substances, as N-acetyl cysteine (119), ubiquinone (122), and melatonin (124), were reported to improve mitochondrial function in aging and the effect was interpreted as an antioxidant action. N-acetyl cysteine prevented, in rat brain, the aged-related changes in mitochondrial gene expression of subunit 39 kDa and ND-1 of complex I, complex IV, subunit α of F1-ATP synthase (complex V) and of adenine nucleotide translocator isofrom 1 (119). Ubiquinone supplementation improved mitochondrial function in heart mitochondria of aged rats (122) and melatonin protected hepatic mitochondrial respiratory activity in senescence-accelerated mice (124).

Mitochondrial oxidative dysfunction is accelerated by many common micronutrient deficiencies. One major mechanism is inhibition of the pathway of heme biosynthesis in mitochondria, which causes a deficit of heme a. Minerals such as iron or zinc, and several vitamin deficiencies, such as biotin or pantothentic acid, increase mitochondrial oxidative dysfunction and turnover through this mechanism. Ames et al. (1) suggested that an optimum intake of micronutrients could tune up metabolism and give a marked increase in health, particularly for the poor, elderly, and obese, at little cost.

Caloric restriction

Limitation in the dietary intake, namely caloric restriction, is a well-established way to extend the life span in mammals (157). Early expectations that caloric restriction would lower metabolic rate have not been confirmed, then if caloric restriction attenuates oxidative damage, it is not by a simple reduction in O2 consumption (147). In liver, heart, brain, and kidney mitochondria, there were no significant effects of caloric restriction in state 4 mitochondrial respiration rate (89) and in mitochondrial ATP content (48). There is now evidence that indicates that caloric restriction acts by decreasing oxidative stress and damage and by increasing antioxidant defenses and repair systems (134). However, the issue is not free of conflicting reports and caloric restriction was reported without enhancing effect in the antioxidant defenses.

Mitochondrial function and caloric restriction are apparently related and that understanding is the main concept of a series of experimental approaches. Caloric restriction was reported to induce a hypometabolic state characterized by decreased reactive oxygen species production and decreased mitochondrial H+ leak, with decreased O2 production in brain mitochondria at complex I without changes in O2 consumption (138). Caloric restricted rats showed structural and functional liver mitochondrial properties (fatty acid pattern, respiratory chain activities, antioxidant levels, and hydroperoxide contents) similar to those of younger rats (3). It was suggested that caloric restriction provides neuroprotection through apoptosis repression by suppressing cytochrome c release and caspase-2 activation, but neither age nor caloric restriction had any effect on caspase-3 and caspase-9 activities (142). Recently, it was reported that caloric restriction induces mitochondrial biogenesis and increases bioenergetic efficiency (97).

In yeast, caloric restriction delays aging by activating Sir2 deacetylase. The expression of mammalian Sir2 (SIRT1) is induced in caloric-restricted rats as well as in human cells that are treated with serum from these animals. SIRT1 deacetylates the DNA repair factor Ku70, causing it to sequester the proapoptotic factor Bax away from mitochondria, thereby inhibiting stress-induced apoptotic cell death. Thus, caloric restriction could extend life-span by inducing SIRT1 expression and promoting the long-term survival of irreplaceable cells (38). SIRT3 is one of the seven mammalian sirtuin homologs of the yeast Sir2 gene, which mediates the effect of caloric restriction in lifespan extension in yeast and Caeno-
rhabditis elegans. Murine SIRT3 is expressed in brown adipose tissue and is localized in the mitochondrial inner membrane. Caloric restriction activates SIRT3 expression in white and brown adipose tissue. Additionally, cold exposure upregulates SIRT3 expression in brown fat, whereas elevated temperature reduces expression. Enforced expression of SIRT3 in HIB1B brown adipocytes enhances the expression of the uncoupling protein UCP1, and a series of mitochondria-related genes. Functionally, sustained expression of SIRT3 would decrease membrane potential and reactive oxygen species production while increasing cellular respiration. In summary, it seems that SIRT3 activates mitochondrial functions and has a role in the adaptive thermogenesis of brown adipose tissue (144).

Mice dietary supplemented with thioproline (l-thiazolidine-4-carboxylic acid), a physiological metabolite of 5-hydroxytryptamine, show a 29% increased median life span and a 23% increased maximal life span, associated with improved mitochondrial function and neurological functions. The thioproline effect seems secondary to caloric restriction, since thioproline induces an anorexic effect with lower food intake and lower body weight (116).

High Spontaneous Neurological Activity

Aging is characterized by a decline of the physiological functions of the central nervous system (61). Associations of the quality of the response to stressful stimuli with longevity and decreased neurodegeneration were reported (61, 115). Mice with high spontaneous neurological activity have 11–14% increased median lifespan and a marked improvement in the performance of behavioral tests (115). Concerning sex difference, female mice with high spontaneous neurological activity showed the longest life span. The longer life span of females is in agreement with the lower mitochondrial production of oxidants in females and with the downregulation of oxidant production by estrogenic hormones (153). Figure 2 shows the relationship between mice survival and the mitochondrial enzyme activities of complex I, complex IV, and mtNOS. Mice were considered with high spontaneous neurological activity by selection according to their performance in two neurological tests. Individual mice were subjected every 2 wk to the tightrope test and the T-shaped maze test (115). In the tightrope test, to evaluate neuromuscular coordination, mice were placed hanging from their anterior legs in the middle of a 60-cm tightrope and the test was considered successful when mice reached the end of the rope in <30 s. In the test to evaluate the spontaneous exploratory and cognitive activities, mice were challenged in a T-shaped maze of 50 cm arms and the test was considered successful when mice moved toward the T-intersection in <30 s. The study showed an inverse statistical relationship between brain oxidative damage and mouse performance in the tests and mitochondrial electron transfer. The higher mitochondrial enzyme activity and the better neurological activity were associated to lower oxidative damage (115).

Moderate Physical Exercise

Exercise has been long considered associated with oxidative stress based on the experimental data showing an increase of oxidative stress markers after high-intensity exercise and on the unsupported assumption that the production of oxygen free radicals is linearly related to the rate of respiration (41, 77). Chronic moderate exercise started at young age in mice increased median lifespan (Fig. 5), decreased oxidative damage and prevented the decline of cytochrome oxidase activity and behavioral performance at middle age but not at old age (Table 1) (113).

Regular physical exercise seems to retard the accumulation of cell damage and the physiological dysfunction that are characteristic of the aging process (131). There is ample evidence of the reduction of skeletal muscle mass associated to aging and of the beneficial effects of regular exercise in increasing muscle mass and strength in elderly individuals. The available evidence extends from experimental animals to humans and from biochemical markers to physiological parameters and behavioral performances (102). A series of reports documented that the beneficial effects of exercise are extended to other organs, such as the heart (19, 113), kidney (113), liver (113), and brain (39). However, aerobic exercise of high intensity and duration is not beneficial for aged rats (118). The positive effects of moderate exercise, observed in heart, kidney, liver, and brain support the concept that the effects involve genomic modulation. Radak et al. (131) suggested that moderate exercise activates DNA repair systems and the resistance against oxidative stress in rat skeletal muscle. Exercise by lifelong voluntary wheel running reduces subarachnoidal and interfibrillar mitochondrial H_{2}O_{2} production in the heart (79). Oxidant production in skeletal muscle is increased in old age and during prolonged exercise, with both the mitochondrial respiratory chain and NADPH oxidase as potential sources, and decreased GSH/GSSG ratios (6).

Overexpression of mitochondrial antioxidant enzymes

The development of transgenic animals that overexpress antioxidant enzymes and other regulatory enzymes in mitochondria and that exhibit increased life span will certainly increase our understanding of the mechanisms of aging. Schürrer et al. (141) reported that transgenic mice that overexpressed human catalase in heart mitochondria have increased median and maximal life span. This transgenic mice strain have reduced age-dependent atherosclerosis and increased genomic stability, as indicated by a decrease in oxidative stress markers and in mitochondrial deletions in heart and muscle. Oxidative damage was reduced, H_{2}O_{2} production and H_{2}O_{2}-induced aconitase inactivation were attenuated, and mitochondrial deletions were reduced. It was disappointing that the Gompertz plot of this transgenic mice strain ran parallel to the wild-type control, indicating a delay in the onset of aging rather than a decrease in aging rate. Nevertheless, the results support the notion of mitochondrial oxidative stress and damage as determinants of both health and life span (141). The relatively large increase in life span resulting from the upregulation of a single gene suggests the possibility that the upregulation of relatively few longevity genes may result in dramatic increases in life span (43).

Previous experiments with transgenic Drosophila melanogaster that overexpressed Cu,Zn-SOD failed to show an increased maximal life span. However, the overexpression of
Cu,Zn-SOD and catalase in these flies extended median and maximal life span (125). Therefore, decreased mitochondrial O$_2^-$ and H$_2$O$_2$ steady-state concentrations appear as able to induce an extended survival.

**HUMAN AGING AND NEURODEGENERATIVE DISEASES**

The increase in human lifespan in the industrialized countries is accompanied by a marked prevalence of neurodegenerative diseases. These diseases are preferential lines of study in gerontology and geriatrics because healthy aging is the first aim in those fields. Human neurodegenerative diseases are characterized by progressive cellular damage which is encompassed by particular neurological deficits once neuronal loss reaches, in most instances, more than half of the neuron population in a given region. For example, Parkinson’s disease is suspected to evolve for years before typical motor signs appear, a moment when there is a loss of dopaminergic neurons of \( \sim 60\% \) in substantia nigra pars compacta.

There is evidence that mitochondrial dysfunction and impairment of the respiratory complexes have a role in the neuronal loss of neurodegenerative diseases. Impaired complex IV activity has been reported in Alzheimer’s disease (29) and decreased complex I activity is usually reported in the substantia nigra of postmortem samples obtained from patients with Parkinson’s disease (108) and in platelets from Parkinson’s patients (100). Also, a decreased activity of complexes I and II has been reported in Huntington’s disease (127).

Inhibition of complex I creates an environment of mitochondrial oxidative damage and of nitration which may lead to opening of the permeability transition pore and to apoptotic cell death (72), or to aggregation of \( \alpha \)-synuclein with the subsequent death of dopaminergic neurons (46). These results show that impairment in complex I activity is central to the pathogenesis of the dopaminergic neuronal demise in Parkinson’s disease (143). Reduced complex I activity predisposes to excitotoxicity by altering ATP levels and by impairing Ca$^{2+}$ homeostasis (45). Reduced ATP levels decrease the activity of plasma membrane Na$^+$/K$^+$-ATPase, resulting in partial neuronal depolarization that decreases the voltage-dependent Mg$^{2+}$ blockade of the N-methyl-D-aspartate glutamate receptor. Under these conditions, even normal levels of extracellular glutamate may cause excitotoxic activation of N-methyl-D-aspartate receptors and elevation of intracellular Ca$^{2+}$. Complex I defects have been reported to disrupt normal Ca$^{2+}$ signaling in neurons (60).

It is to be expected that prevention or slowing down the processes of mitochondrial dysfunction upon aging will decrease the neurological deficits in aged people.

**CONCLUSIONS AND PERSPECTIVES**

It is now clear that mammalian life span is negatively related to the mitochondrial production of oxidizing free radicals and that dysfunctional mitochondria determine mitochondrial and cellular turnover. Mitochondrial impairment and cellular dysfunction upon aging determine tissue physiological function. Tissues, such as brain and brain areas that have a slow turnover for their mitochondria and mitochondrial components, are driven to a physiological deficit by mitochondrial-dependent apoptosis.

Aged mitochondria show a selective diminished activity of the enzymes that are integral and constitutive proteins of the inner mitochondrial membrane. Complexes I and IV and mt-NOS are selectively affected in aging and constitute markers of tissue aging. These three enzymes interact by physical contact, according to the model of the supercomplexes of the respiratory chain. The enzyme mtNOS has been reported associated to complexes I and IV by evidence of complementary sequences and immuno-coprecipitation (55).

The slower rate of mitochondrial electron transfer in aging favors the mitochondrial generation of O$_2^-$ by complex I, and produces a positive feedback between complex I inhibition and the mitochondrial production of O$_2^-$ and peroxyynitrite.

Mitochondrial biogenesis seems regulated by the signaling given by NO and H$_2$O$_2$ diffusion from mitochondria to the cytosol. The study of mitochondrial NO and H$_2$O$_2$ production and diffusion as a function of aging will contribute to the understanding of mitochondrial biogenesis, cell proliferation and apoptosis in determining the physiological failure of aging tissues. The diffusion of mitochondrial NO and H$_2$O$_2$ depends on the mitochondrial metabolic state, with rates that are different in state 4 and in state 3. In the case of NO diffusion there is an exponential dependence on the membrane potential and in the case of H$_2$O$_2$ diffusion the process is regulated by the redox state of the respiratory chain. Moreover, the regulation of mtNOS activity by membrane potential makes mtNOS a regulable enzyme that in turn regulates mitochondrial O$_2^-$ uptake and H$_2$O$_2$ production. The altered signaling by mitochondrial NO and H$_2$O$_2$ appears as a likely explanation for the decreased mitochondrial biogenesis in aging, a process that certainly contributes to cellular energy deficits, apoptosis, and tissue physiological failure in aging.

**GRANTS**

This study was supported by Grants FIS PI021354 and FIS PI050636 from Ministerio de Sanidad and Consumo de España, Fondo de Investigación Sanitaria, Instituto de Salud Carlos III; by Plan Andaluz de Investigación 2003–2005 (CTS-194) of Spain, and by Grant B-027 from the University of Buenos Aires, Agencia Nacional de Promocion Científica y Tecnológica Grant PIP 2271-00, and Consejo Nacional de Investigaciones Científicas y Técnicas of Argentina Grant PIP 6320-OY.

**REFERENCES**


DYSFUNCTIONAL MITOCHONDRIA IN AGING


