Mitochondrial Metabolism in Aging Heart
Edward J. Lesnefsky, Qun Chen, Charles L. Hoppel

Abstract: Altered mitochondrial metabolism is the underlying basis for the increased sensitivity in the aged heart to stress. The aged heart exhibits impaired metabolic flexibility, with a decreased capacity to oxidize fatty acids and enhanced dependence on glucose metabolism. Aging impairs mitochondrial oxidative phosphorylation, with a greater role played by the mitochondria located between the myofibrils, the inter fibrillar mitochondria. With aging, there is a decrease in activity of complexes III and IV, which account for the decrease in respiration. Furthermore, aging decreases mitochondrial content among the myofibrils. The end result is that in the inter fibrillar area, there is ≈50% decrease in mitochondrial function, affecting all substrates. The defective mitochondria persist in the aged heart, leading to enhanced oxidant production and oxidative injury and the activation of oxidant signaling for cell death. Aging defects in mitochondria represent new therapeutic targets, whether by manipulation of the mitochondrial proteome, modulation of electron transport, activation of biogenesis or mitophagy, or the regulation of mitochondrial fission and fusion. These mechanisms provide new ways to attenuate cardiac disease in elders by preemptive treatment of age-related defects, in contrast to the treatment of disease-induced dysfunction. (Circ Res. 2016;118:1593-1611. DOI: 10.1161/CIRCRESAHA.116.307505.)

Key Words: cardiolipin ■ electron transport chain complex proteins ■ fatty acid oxidation complex ■ oxidative phosphorylation ■ reactive oxygen species
Nonstandard Abbreviations and Acronyms

ALCAT-1 Acyl-CoA:lysocardiolipin acyltransferase-1
ASK-1 apoptosis signal-regulating kinase 1
CPT carnitine palmitoyltransferase I
CR caloric restriction
ETC electron transport chain
FAO fatty acid oxidation
IFM interfibrillar mitochondria
MAO monoamine oxidase
MPTP mitochondrial permeability transition pore
mtDNA mitochondrial DNA
NADH nicotinamide adenine dinucleotide
Nrf2 nuclear factor erythroid 2–related factor 2
OXPHOS mitochondrial oxidative phosphorylation
PDC pyruvate dehydrogenase complex
PDH pyruvate dehydrogenase
PDK pyruvate dehydrogenase kinase
Qo ubiquinol-binding site
ROS reactive oxygen species
SSM subsarcolemmal mitochondria

Metabolism and Metabolic Flexibility in the Aging Heart

OXPHOS is the main energy source for the myocardium. In cardiac mitochondria, fatty acids and carbohydrate are the 2 main classes of substrates used to generate ATP through OXPHOS. Under physiological conditions, the heart receives ≈70% of its energy from FAO and 30% from metabolism of carbohydrates via pyruvate and lactate. Under different conditions, the ratio of energy supply from fatty acid and carbohydrate is dynamically adjusted, indicating that the heart has a flexibility of substrate usage. The effect of aging on substrate flexibility is incompletely understood.

Glycolysis yields pyruvate in the cytoplasm. To enter the mitochondria, pyruvate first traverses the mitochondrial outer membrane via the voltage-dependent anion channel and then the inner membrane via monocarboxylate transporter system. Once in the mitochondrial matrix, pyruvate dehydrogenase (PDH) metabolizes pyruvate and generates nicotinamide adenine dinucleotide (NADH) and acetyl-CoA. From acetyl-CoA, citrate synthase produces citrate using oxaloacetate from the tricarboxylic acid cycle located in the matrix space. In addition to pyruvate, other tricarboxylic acid cycle substrates are regulated by the action of inner membrane transporters. PDH complex (PDC), a gatekeeper for mitochondrial glucose oxidation, is a key enzyme complex that modulates the competition between fatty acid and carbohydrate metabolism. PDH activity is regulated by PDH kinases (PDKs) that respond to allosteric modifiers derived from glycolysis and FAO. NADH and acetyl-CoA derived from FAO (and pyruvate oxidation) activate PDKs, which leads to PDH inhibition, whereas pyruvate generated from glycolysis deactivates the PDKs, in turn activating PDH. PDK activity is regulated via post-translational modifications, including phosphorylation and lysine acetylation. PDC regulation is critical to regulation of the metabolic flux of carbohydrate in pathophysiological states. In aging, post-translational modification by PDK via altered phosphorylation increases flux through PDC, favoring mitochondrial metabolism that leads to enhanced glucose oxidation. Thus, there is increased capacity for glucose oxidation by mitochondria via enhanced PDC-mediated pyruvate metabolism. Also, there is increased capacity for glucose oxidation by mitochondria via enhanced PDC-mediated pyruvate metabolism. When PDH activity is measured without inhibiting PDK during the assay, apparent PDH activity is decreased in aged rat hearts, but the total activity was not measured.

Fatty acids are oxidized mainly within mitochondria. β-oxidation of fatty acids occurs in the matrix after activation and transport of fatty acids into the matrix via contact sites. β-oxidation also produces NADH and reduced flavin adenine dinucleotide (FADH2). FAO is decreased in the aging heart. PDK4 content is increased in the aged heart, favoring increased glucose oxidation at the expense of FAO.

In contrast, the enzymes involved in the regulated transport of long-chain fatty acids into mitochondria and oxidation are unaltered despite decreases in peroxisome proliferator–activated receptor-γ activity. The long-chain fatty acyl-CoA is first converted to the long-chain acylcarnitine through carnitine palmitoyltransferase I (CPT-I). The long-chain acylcarnitine is transported into the mitochondrial matrix across the inner mitochondrial membrane by carnitine–acylcarnitine translocase. Then, the long-chain acylcarnitine is converted back to matrix long-chain acyl-CoA by CPT-II. Among these enzymes, CPT-I is the rate-limiting step in regulating FAO. There are 2 isoforms of CPT-I: liver-type isoform and muscle-type isoform. The dominant CPT-I isoform in the adult heart is the muscle-type isoform, which is sensitive to malonyl-CoA inhibition. Malonyl-CoA is produced through carboxylation of acetyl-CoA by acetyl-CoA carboxylase and is converted back to acetyl-CoA by malonyl-CoA decarboxylase. The increased pyruvate oxidation results in inhibition of FAO by increasing acetyl-CoA and subsequent malonyl-CoA generation. In contrast, increased FAO can inhibit pyruvate oxidation by the generation of acetyl-CoA. Thus, there is an interaction between FAO and glucose metabolism. Aging does not alter CPT-I content nor phosphorylation nor is there a shift of isoform.

We found no change in CPT-I velocity or sensitivity to malonyl-CoA in either population of heart mitochondria. In
contrast, the Hagen laboratory described a decrease in palmitoyl-CoA oxidation and CPT-I activity only in IFM. We think that the decreased palmitoyl-CoA oxidation occurs as a result of the IFM electron transport chain (ETC) defects; nagarse was used to isolate IFM and is associated with a decrease in CPT-I activity, whereas we use trypsin without an effect on CPT-I. Acetyl-l-carnitine supplementation reverses the age-related decline in CPT1 activity in IFM without changing the l-carnitine content in the rat heart.

Fatty acid metabolism is altered in disease conditions that could interact with age-induced defects. In an in vitro working model, FAO is decreased with compromised cardiac function in aged mouse hearts exposed to high afterload. Ischemia leads to decreased malonyl-CoA content and increased FAO by increasing CPT-I activity. The circulating fatty acid concentration also is increased after ischemia.

The harnessing of chemical energy by mitochondria as an inner membrane potential requires the inner membrane to have tightly controlled permeability. The inner membrane contains ion channels and transporters that regulate proton and ion fluxes, as well as the uptake of substrates and the translocation of small molecules into and out of the matrix.

The phosphorylation apparatus harnesses the electrochemical energy stored in the inner membrane proton gradient to phosphorylate ADP by complex V. Uncoupling of electron flux from ADP phosphorylation occurs with dissipation of the electrochemical gradient. Mechanisms to dissipate the electrochemical gradient under physiological circumstances include activation of uncoupling proteins that span the inner membrane and regulated proton slip within ETC complexes. Membrane potential controls the rate of respiration because in complexes I and III, electron flow within the complex includes a segment where electrons move counter to the membrane potential. In disease settings, dissipation of the electrochemical gradient occurs because of breaches in the inner membrane or damage to complex V that allow back diffusion of protons down their electrochemical gradient not coupled to phosphorylation. As discussed below, damage to inner membrane phospholipids, especially cardiolipin, and activation of the mitochondrial permeability transition pore (MPTP) are mechanisms that lead to pathological uncoupling of respiration.

Respiratory defects present in mitochondria are reflected in the rate of global respiration in permeabilized muscle fibers. Although only IFM mitochondria are affected by age, global respiration in the fibers is decreased. Decreases in the rate of oxidative phosphorylation with substrates that selectively donate to complex III or complex IV are observed, supporting the effect on global respiration in the myocyte of the age-induced decrease in respiration in IFM.

IFM isolated from 24- and 28-month-old Fischer 344 rat hearts exhibit decreased OXPHOS, whereas respiration in SSM is unaffected. Although the ADP-stimulated rates of respiration are decreased in IFM, oxygen consumption remains tightly coupled to ADP phosphorylation.

Figure 1. Schematic of the interfibrillar mitochondrial defects in the aged heart. ETC indicates electron transport chain; IMM, mitochondrial inner membrane; NADH, nicotinamide adenine dinucleotide; PPL, phospholipid, proposed defect affecting subunit Yll in complex IV; and Q, ubiquinone; Q, ubiquinol-binding site on cytochrome b, with proposed defect in Y132. Illustration credit, Ben Smith.
in uncoupled respiration localizes the defect to the ETC. The decrease in respiration using selective donors to complex IV localizes a defect at least to cytochrome oxidase, the most distal complex, as discussed below. Controversy on the presence of age-related defects was based on the fact that in some laboratories, no defect was found when isolation techniques yielded only SSM, whereas combined mitochondrial populations were studied in different laboratories and in the latter case, the IFM defect, is fact, is masked to a great extent by the presence of unaffected SSM (Figure 1). Age-related decreases in FAO and cytochrome oxidase activity were localized to IFM. Previous studies of mitochondrial populations containing only SSM found, as expected, that ROS production and protein import were unaltered by age. The finding of defects localized to IFM is not unique to aging and is also observed in diabetes mellitus and cardiomyopathy. Decreased OXPHOS capacity has been observed in a variety of rat strains, as well as in murine models of aging. The study of IFM, in which key aging-related alterations in OXPHOS reside, without the confounding effects of admixed, unaltered SSM, has facilitated the study of the contributions of mitochondria to age-related dysfunction in the heart.

The identification of each population is based on the location in the myocyte and the documentation of selective isolation based on electron microscopy. Molecular markers for each population remain elusive. Unfortunately, there have not been studies of the global mitochondrial proteome to compare SSM and IFM in adult and aged hearts, unlike in the diabetic heart. Nonetheless, responses at the molecular level differ between the 2 populations. In a proteomic study of the acetylated proteins in each population, differences between SSM and IFM were observed. The differences included outcomes from both endogenous acetylation/deacetylation and responses to chemical/nonenzymatic acetylation. Of note, SIRT3 content was decreased in SSM but remained unaltered in IFM.

It remains a possibility that the alterations in each population arise as a result of differences in regional environments within the cardiac myocyte. Global ATP contents in adult and aged hearts are similar. The ATP content in the subsarcolemmal region where SSM reside could differ from that in the remainder of the myocyte. IFM are in proximity to t-tubules in the sarcomeres, which may increase the exposure of the IFM to calcium. The relative interaction of SSM versus IFM with sarcoplasmic reticulum via mitochondria-associated membranes is also unknown. The regional environment may provide a milieu for selective defects observed in IFM in genetic and diabetic cardiomyopathies, as well as with aging because of the impairment of the removal of damaged mitochondria from this region. The regional differences in mitochondrial function, either as a result of damage to the mitochondria by external mechanisms or regional impairment in function, may be attenuated by the presence of connections between mitochondria in subsarcolemmal and interfibrillar regions.

The role of regional differences within the myocyte because of genetic deletion or overexpression of nuclear-encoded mitochondrial proteins has not been considered. It would initially seem that both SSM and IFM populations would be affected by the absence or overexpression of a nuclear-encoded mitochondrial component protein to a similar extent. Thus, the study of alteration in mitochondrial function that involved only SSM or IFM in response to gain of function or loss of function of a mitochondrial protein encoded by the nuclear genome would seem to be irrelevant. However, in light of the potential for mitochondrial damage because of regional-specific stresses, or, possibly, defective generation or removal of mitochondria specific to one region of the myocyte, it is plausible that despite the similar gain or loss of a mitochondrial component, that dysfunction may be manifest in only one subpopulation of mitochondria.

**Mitochondrial Morphology in the Aging Heart**

**Subsarcolemmal Versus IFM**

Using transmission electron microscopy to examine heart ventricular tissue, the presence of 2 spatially distinct populations of mitochondria is apparent. Using a Polytron homogenizer, skinned fibers are produced: these lack surface mitochondria but retain mitochondria trapped between the myofibrils. This observation provides morphological evidence of the 2 disparate types of mitochondria: 1 type clustered beneath the sarcolemma (SSM) and the other type imprisoned by myofibrils. As supported by rigorous studies of the recovery of mitochondrial marker enzymes, the decreased content of IFM isolated from aged hearts reflects a true decrement present in myocardium. In contrast, the content of SSM is unaltered with age. Thus, the decreased content of IFM magnifies the respiratory defect present in IFM. Regional differences in mitochondrial function have been observed in multiple species, including mouse, hamster, guinea pig, rabbit, and dog. Aging defects in mitochondrial function have been observed in mice and humans although studies have not yet addressed if defects are present in only 1 subpopulation.

**Mitochondrial Morphology in the Aging Heart: Cristae and Contact Sites**

The cartoon in Figure 2 depicts a cardiomyocyte to illustrate the location of SSM under the sarcolemmal membrane and IFM between the myofibrils. Structural differences of the 2 populations of mitochondria in adult and aged Fischer 344 rat hearts using transmission electron microscopy are not apparent in situ or in isolated organelles (Figure 3A and 3B). However, osmium-extracted cardiomyocytes examined by high-resolution scanning electron microscopy revealed differences in the 3-dimensional structure of cristae. As shown in Figure 4A for adult rat hearts, the sarcolemma is clearly observed; immediately, beneath the sarcolemma are the SSM (shown by the arrow to Figure 4B). The empty spaces within the fiber represent areas previously containing myofibrils, which have been extracted by the osmium process. Around these voids are the organelles, the IFM, which are stacked as shown in Figure 4A. The arrow points to an IFM at greater magnification (Figure 4C). The SSM contain largely lamelliform cristae (Figure 4B), but in contrast, the IFM have mostly tubular cristae (Figure 4C). Using high-resolution scanning electron microscopy, in the 24-month-old Fischer 344 rat, the
isolated SSM are mainly lamelliform (Figure 3C), whereas the IFM contain predominantly tubular cristae (Figure 3D).46,47 There are no age-related alterations in cristae morphology that accompany the biochemical defects. In this study, isolated mitochondria show relatively more plasticity with rearrangement of the cristae morphology, but again, there are no structural differences between the 2 ages for either population of mitochondria. However, a recent study of 24-month-old Wistar and OXYS rats using transmission electron microscopy described alterations in cristae structure with age.48 The different results could be because of the different strains of rat using different fixation methods.24

Cardiolipin: Membrane Building Block and Signaling Component
Cardiolipin is a diphosphatidylglycerol lipid found largely in the mitochondrial inner membrane and is required for optimal energy generation.70,49 Cardiolipin is highly enriched in oxidatively sensitive linoleic acid (C18:2).50 Aging did not alter the content or composition of cardiolipin in SSM or IFM from elderly 24-month-old Fischer 344 rats compared with adult rats.51 Cardiolipin content was documented by analytic phosphate assay with recovery studies.51 The acyl-group composition and molecular species of cardiolipin also were unaltered in aged hearts. In contrast, Paradies et al30,32 have described a decrease in cardiolipin content with aging estimated by ultra violet absorbance using a mixed population of cardiac mitochondria. However, in our hands, cardiolipin content using this approach was also unchanged in IFM with aging.51 Thus, although others propose decreases in cardiolipin content with aging leading to altered membrane fluidity in the inner membrane,52,53 the role of cardiolipin content as a mechanism of age-induced defects in electron transport remains controversial.

Cardiolipin undergoes age-specific modification in response to the stress of ischemia in the aged heart.54,55 Consistent with a lipid peroxide mechanism, the new molecular species involves the addition of 48 Da to a single linoleic acid acyl group, consistent with the formation of a hydroxyl lipid peroxide. Products of linoleic acid with molecular weight increased by 48 Da are formed during the mitochondria-driven peroxidation of linoleic acid.56,57 Cardiolipin with a molecular weight also increased by 48 Da is present during in situ oxidative stress in other systems.58 The oxidation of cardiolipin provides strong support for the presence of age-enhanced oxidative damage to mitochondria during ischemic stress in the aged heart.

The formation of a single product, rather than a mixture of oxygenated linoleic residues,54 suggests that a specific, perhaps enzymatic, mechanism of peroxidation occurs in contrast to stochastic chemical peroxidation. Cytochrome c can alter its interaction with cardiolipin,59 leading to a conformational change that favors the oxidation of a key methionine ligand of the cytochrome c heme, resulting in the formation of a new
peroxidase activity. Cardiolipin is oxidized by this newly generated cytochrome c peroxidase.\textsuperscript{58,60} The key oxidative modification of cytochrome c required for acquisition of peroxidase activity occurs during ischemia,\textsuperscript{54,55,61} targeting oxidative modification as a plausible mechanism.

Alteration in cardiolipin species often results from defective remodeling of cardiolipin.\textsuperscript{60} Under oxidative conditions, monolysocardiolipin is generated via hydrolysis of an oxidized C18:2 residue. The monolysocardiolipin then undergoes reacylation via a process of salvage remodeling.\textsuperscript{60} The enzyme, tafazzin, remodels nascent cardiolipin during de novo synthesis to the required (C18:2)\textsubscript{4} species.\textsuperscript{62,63} Tafazzin, however, seems to contribute a minor, if any, step in salvage remodeling of cardiolipin in the mature heart in response to disease-induced remodeling.\textsuperscript{60,65,66} Because secondary remodeling of cardiolipin by ALCAT-1 is extramitochondrial, it is unlikely that regional defects would require mitochondria–endoplasmic reticulum interactions. Because secondary remodeling of cardiolipin by ALCAT-1 is extramitochondrial, it is unlikely that regional defects would be present. Thus, the lack of altered remodeling in IFM from the aged heart is consistent with ALCAT-1 as the major mechanism of remodeling.

Oxidation of cardiolipin decreases the function of ETC complexes,\textsuperscript{73} disrupts the bilayer arrangement of the inner membrane,\textsuperscript{20,60} and favors the release of cytochrome c to initiate cell death.\textsuperscript{58,72} Cardiolipin oxidation will likely continue to emerge as a key mechanism of the enhanced mitochondrial-dependent injury that occurs in the aged heart in response to pathological stress and is a potential mechanism of the augmented age-enhanced susceptibility to superimposed cardiac disease.

SS-31 (a synthetic peptide) can directly bind to cardiolipin on the inner membrane and improve the efficiency of the ETC. SS-31 inhibits the function of the cytochrome c cardiolipin peroxidase.\textsuperscript{73} SS-31 treatment increases mitochondrial efficiency in aged skeletal muscle, decreases cardiac injury during ischemia–reperfusion, and improves mitochondrial function in heart failure.\textsuperscript{73} These actions support the pathogenic role of cardiolipin oxidation by the cytochrome c peroxidase in the heart under stress.

**Age-Induced Defects in Electron Transport**

The ETC is composed of 4 multisubunit enzyme complexes, complexes I–IV (Figure 5). Electron transfer down the redox potential gradient from NADH or FADH\(_2\), to oxygen is coupled to the active transport of hydrogen ions from the matrix to the cytosolic side of the inner membrane by complexes I, III, and IV.\textsuperscript{74} Complex I oxidizes NADH, with sequential electron flow to coenzyme Q, complex III, cytochrome c, and ultimately to cytochrome oxidase (complex IV), the latter reducing oxygen to water. The complexes of the ETC are organized into larger respirasomes (supercomplexes)\textsuperscript{75,76} to optimize channeling of reducing equivalents between the components. The organization of respirasomes is altered in the aged heart,\textsuperscript{77} which can result in functional defects in electron transport in the absence of post-translational modification or decreased content of an individual ETC complex. For example, although OXPHOS of substrates that enter through complex I is decreased, the site of ETC defects in complexes III and IV (discussed below) accounts for the decrease. Complex I enzyme activity remained unaltered by age in rat\textsuperscript{39} and mouse hearts.\textsuperscript{79} Functional decreases in complex I might be related to alteration in complex I containing respirasomes,\textsuperscript{77} potentially related to oxidative damage to cardiolipin.\textsuperscript{79} Such alterations in supercomplex organization are observed after the onset of congestive heart failure.\textsuperscript{80}

**Cytochrome Oxidase (Complex IV)**

The aging defect in cytochrome oxidase activity occurs as a result of an altered inner membrane environment of the mitochondria with increased docosahexaenoic and arachidonic contents in cardiolipin displayed unaltered rates of OXPHOS.\textsuperscript{69} The presence of nonlinoleate acyl groups disrupts the compact configuration of (C18:2)\textsubscript{4} cardiolipin, paradoxically increasing the oxidative sensitivity of the asymmetrical cardiolipin.\textsuperscript{20} ALCAT-1 is located in the endoplasmic reticulum,\textsuperscript{20} suggesting that secondary cardiolipin remodeling may require mitochondria–endoplasmic reticulum interactions.
Activity is recovered by the addition of phospholipid liposomes, including cardiolipin. The finding of unaltered cardiolipin content and composition in IFM, despite the presence of a functional defect, supports the presence of a probable defect in cardiolipin in the immediate environment of cytochrome oxidase. Such a defect likely effects the organization of cytochrome oxidase into supercomplexes, with subsequent decreased enzyme activity. The altered membrane environment leads to a decrease in fluidity of the inner membrane. Altered phase behavior of the inner membrane with age may occur because of the depletion of n-3 acyl groups or because of oxidative damage to membrane phospholipids.

In addition to the phospholipid environment defect, there is a functional defect about the subunits of cytochrome oxidase. The content of subunits is unaltered with age as identified by analytic immunoblotting. In contrast, immunoelectron microscopy revealed a 25% reduction in cytochrome oxidase subunit VIIa selective to IFM in the aged heart. The absence of immunoreaction of the VIIa subunit in situ assessed by immunoelectron microscopy was not due to a reduction in protein but rather to a masking phenomenon or to an in situ change in protein structure affecting cytochrome oxidase.

Decreased cytochrome oxidase activity has the potential not only to impair energy production but also to enhance cytotoxicity. Attenuated flux through cytochrome oxidase increases the relative reduction of upstream redox centers in complexes I and III, favoring ROS production as discussed below. In addition, decreased cytochrome oxidase activity activates cell stress responses, in part, via the activation of endoplasmic reticulum stress. Cytochrome oxidase content and activity are decreased in the aged human heart.

**Complex III**

Complex III activity is decreased only in IFM in the aged heart. Mammalian complex III is composed of two 11-subunit monomers, with 3 of these subunits, cytochrome b, cytochrome c1, and the iron-sulfur protein, involved in electron transfer. After oxidation of the substrate, ubiquinol, there is a concerted transfer of electrons to cytochromes b and c1 in a bifurcated fashion mediated by motion of the iron-sulfur protein. Based upon structure–functional relationships of electron flow within complex III, the study of mutant complex III phenotypes in bacteria, and the three-dimensional crystal structure, the study of partial reactions of complex III was utilized to localize the defect to the ubiquinol-binding site (Qo) within cytochrome b. The use of specific chemical inhibitors further localizes the defect to the proximal domain of the Qo site. By comparison to phenotypes that result from site-directed mutagenesis in the bacterium *Rhodobacter spheroides* (bacteria allow straightforward site-directed mutagenesis of cytochrome b, the region of the age-induced defect can be deduced. The aging phenotype of complex III consists of decreased maximal activity, preserved electron paramagnetic resonance (EPR) signal, an increased leak through myxothiazol blockade to reduce cytochrome b, and preserved inhibition by stigmatellin. Amino acids in the Qo site are highly conserved from *R. spheroides* to mammalian cytochrome b. Point mutations with resistance to myxothiazol but not to stigmatellin (A126, Y132, V133, M139, G143, and F275) are potential sites of the age-related defect. In addition to myxothiazol resistance, mutation at Y132 also decreases complex III activity but yet maintains the EPR signal. For this reason, Y132 can be considered as a potential site of age-induced oxidative modification to the Qo site, a mechanism of the aging phenotype of complex III. Proteomic evaluation of the Qo site, including Y132, is limited by the difficulty of proteomic approaches to this most hydrophobic region of the markedly hydrophobic cytochrome b subunit. Current proteomic techniques should provide approaches to study this key region of age-induced alteration in electron transport. Cytochrome b is encoded by mitochondrial DNA (mtDNA), so mtDNA mutations with age could alter the composition of the Qo site with subsequent alteration in complex III activity and age-induced pathophysiology. Unfortunately, because it is a mitochondrial-encoded protein,
direct molecular manipulation to test the role of Y132 is not feasible because of the multiple copies of mtDNA present.

Complex V

The activity of complex V decreases with age, potentially decreasing the efficiency or coupling of OXPHOS. Localization of the site of the defect within complex V remains unknown. Age-induced alteration of complex V is of contemporary interest because complex V, recently identified as the likely locus of the MPTP, has an increased propensity to open, even in the baseline state, in the aged heart. Nonetheless, uncoupled respiration is decreased by age in IFM in aged hearts, localizing the defects that limit the rate of phosphorylation. 

mtDNA With Age and Effect on OXPHOS

Accumulation of mtDNA deletions in cells leads to respiratory chain deficiency. mtDNA copy number is decreased in aged skeletal muscle and liver compared with adults. However, mtDNA copy number is not altered in the aged heart, including SSM and IFM. However, analysis of transcripts of catalytic mtDNA-encoded subunits in aged hearts is suggestive of increased mtDNA mutation with age. The downregulation of the 8-oxodeoxyguanosine glycosylase mouse model with defective base excision repair in mitochondria clearly supports the accumulation of oxidative damage to mtDNA with age. The accumulation of oxidative damage to mtDNA, likely in part from mitochondria themselves as discussed below, may be a contributing mechanism to age-induced impairment of mitochondrial metabolism. Oxidative damage to mtDNA leads to point mutations and eventual double-strand breaks, resulting in large deletions. However, the accumulation of point mutations with age or in mice heterozygous for a proofreading-defective mitochondrial polymerase-γ (mitochondrial mutator heterozygotes) did not affect lifespan or cardiac function. In contrast, mice homozygous for proofreading-defective polymerase-γ (Polγmut(mut)) exhibit a marked increase in mtDNA mutation burden and cardiac dysfunction with an increase in the prevalence of cytochrome oxidase negative myocytes that are likely to exhibit defective mitochondrial respiration. Of interest, aged human hearts have an increased frequency of cytochrome oxidase negative myocytes. Damage and deletion of mtDNA can give rise to nonhomogeneous mtDNA composition between mitochondrial populations, thus increasing mitochondrial heteroplasmy. Accumulation of mtDNA mutations with age has functional consequences for mitochondria and the heart. There is increased protein oxidation in heart tissue and increased programmed cell death. The finding of an age-related defect in IFM localized to mtDNA-encoded cytochrome b could imply mtDNA mutation. Altered mtDNA transcription with age may also indicate defects in mtDNA regulation at levels above the mitochondrial genome itself. Recently, signal transducer and activator of transcription 1 (STAT1) localized to mitochondria was found to affect mtDNA replication. Potential defects in TFAM (mitochondrial transcription factor A) transcription, nucleoid (the mtDNA in aggregate) function may also affect mtDNA replication and stability. Although previous studies support the lack of change in mtDNA copy number, the effect of mtDNA number and mutation burden, especially differences between the 2 populations of mitochondria, are worthy of reassessment in the current era of deep sequencing.

Production of ROS by Mitochondria in the Aged Heart

Sites of Production of Oxidants Within the ETC

Aging increases ROS production from mitochondria in multiple cardiac models. Complexes I to III are potential sources for ROS production by the ETC, with complex I producing ROS by both forward and reverse electron transport. Two mechanisms combine to increase ROS production from mitochondria in aged tissues. First, decreased flux through the ETC increases the reduction of upstream complexes, especially complexes I and III, increasing the probability that reduced redox centers will directly react with molecular oxygen to generate ROS. Thus, the fraction of electron flux that forms ROS is greater during state 4 ADP-limited respiration than during state 3 ADP-stimulated respiration. Dissipation of the inner membrane potential decreases the efficiency of phosphorylation; the increased rate of electron flux through the ETC decreases the probability that a reduced redox center will directly react with molecular oxygen. ROS production from complex III is especially responsive to modulation of inner membrane potential. Thus, the decrease in respiration through cytochrome oxidase present in IFM from the aged heart favors the relative reduction of complexes I and III with greater ROS production. Second, aging-induced modification of individual ETC complexes alters the function of the complex to directly favor ROS production as seen with complex III in IFM.

Complex III is a major site for net ROS release from mitochondria. ROS produced at the quinol oxidation site (Qo center) are generated at the cytosolic face of the inner membrane and are released into the intermembrane space, ultimately favoring release from mitochondria. The aging defect at cytochrome b in the Qo site of complex III in IFM predicts the increase in net production and release of ROS from IFM isolated from aged hearts. The net release of H$_2$O$_2$ was increased in IFM isolated from aged rat hearts compared with adult controls, whereas SSM, without the aging defect in complex III, showed no increase in ROS production. In line with increased ROS production within IFM, indicators of oxidative stress increased in these organelles during aging. The increased oxidative stress to mitochondria may underlie the apparent tendency of mitochondria from the aged heart to undergo permeability transition, leading to cytochrome c release as discussed below, with subsequent initiation of programmed cell death.

The pathway of release of ROS generated by the Qo site of complex III is the mitochondrial contact site. Contact sites are in close association with sites of mitochondria–endoplasmic reticulum interaction. Thus, superoxide directed outward from mitochondria is likely to affect mitochondria-associated membranes and endoplasmic reticulum as the proximate target.
ROS production from complex I can increase in 2 ways: by a blockade of forward electron flow from NADH-linked substrates via inhibition of enzyme activity or via blockade at distal sites in the ETC,\textsuperscript{121,122,127,133–135} including cytochrome oxidase. Alternatively, the induction of reverse electron flow from complex II to complex I using succinate as a substrate leads to ROS production.\textsuperscript{120,122,136–138} Reverse electron flow requires mitochondrial membrane potential.\textsuperscript{137} Reverse flow can occur in the presence of simultaneously available complex I and complex II substrates; thus it is of probable physiological relevance.\textsuperscript{120}

In addition to the ETC, p66\textsuperscript{shc} and monoamine oxidase (MAO) are sources that generate ROS in mitochondria. The p66\textsuperscript{shc} is a ubiquitously expressed adaptor protein\textsuperscript{139} located within the mitochondrial intermembrane space. Molecular oxygen is reduced to H\textsubscript{2}O\textsubscript{2} in a redox center of p66\textsuperscript{shc} coupled with the oxidation of cytochrome c.\textsuperscript{140} Ablation of p66\textsuperscript{shc} increases the resistance to oxidative stress and extends the life span of mice.\textsuperscript{139} Inhibition of p66\textsuperscript{shc} also decreases cell injury during ischemia–reperfusion through a reduction of oxidative stress.\textsuperscript{141–143} However, knockout of p66\textsuperscript{shc} increases cell injury in the mouse heart subjected to reperfusion after a short period of ischemia.\textsuperscript{144}

MAO is a flavoenzyme located in the outer mitochondrial membrane. MAO includes 2 isoforms (MAO-A and MAO-B) that generate H\textsubscript{2}O\textsubscript{2} when MAO oxidatively breaks down neurotransmitters, such as norepinephrine, epinephrine, and dopamine.\textsuperscript{145} Oxidative stress induced by MAO contributes to cardiac injury\textsuperscript{146} and to muscle dystrophy.\textsuperscript{147} MAO-B, but not MAO-A, is increased in aged mouse hearts.\textsuperscript{148} Interestingly, only inhibition of MAO-A but not MAO-B can decrease MAO-mediated H\textsubscript{2}O\textsubscript{2} generation in the aged heart.\textsuperscript{149} MAO is a source of oxidative stress during aging.

The increased production of ROS by mitochondria leads to greater oxidative damage within mitochondria, including protein sulfhydryl oxidation, lipid peroxidation, and mtDNA damage.\textsuperscript{129,150} A relative increase in the uncoupling of respiration,\textsuperscript{118,119,151} as well as an increase in antioxidant enzyme contents, provides complimentary mechanisms to decrease oxidative damage. Thus, the initial target of mitochondrial ROS production is the mitochondria themselves. Next, ROS, including superoxide, can be released by traversing anion channels and contact sites,\textsuperscript{115,126,127} possibly targeting structures adjacent to mitochondria. Recent work has highlighted key effectors of oxidants produced by the ETC, rather than merely stochastic oxidant release from mitochondria. Examples of oxidant-dependent targeted injury include the activation of MPTP opening, generation of the cytochrome c cardiolipin peroxidase, and activation of the oxidant-dependent apoptosis signal-regulating kinase 1 (ASK-1) signaling cascade.

Overexpression of catalase within mitochondria attenuates cardiac aging, providing direct evidence that ROS generated from mitochondria is detrimental to aged hearts.\textsuperscript{152} Although this is not always the case, this is best documented in invertebrate species,\textsuperscript{156} including Caenorhabditis elegans. Multiple genotypes that exhibit either decreased production or enhanced disposition of ROS exhibit increased lifespan.\textsuperscript{154,155} In mammalian systems, clear evidence of the potentially protective low levels of signaling ROS production is more difficult to demonstrate. In fact, signaling ROS are critical for the mechanism of classic ischemic preconditioning; yet, as discussed below, the aged heart is relatively refractory to the protection of ischemic preconditioning, perhaps because of the excessive tonic production of ROS.

Nuclear factor-erythroid 2–related factor 2 (Nrf2) is a redox-sensitive transcription factor. Nrf2 is activated in response to oxidative stress and leads to subsequent upregulation of antioxidants.\textsuperscript{156} Surfeit locus protein 1 is a nuclear-encoded chaperone protein and aids the assembly of the subunits of complex IV. Knockout of the surfeit locus protein 1 leads to decreased activity of complex IV and the OXPHOS rate. The defect of complex IV in surfeit locus protein 1 knockout mice activates mitochondrial biogenesis and Nrf2 expression,\textsuperscript{157} in line with a cytochrome oxidase defect that impairs energy production and enhances ROS production. Expression of Nrf2 is decreased in elderly patients.\textsuperscript{158} Strategies to stimulate Nrf2 expression and enhance endogenous antioxidants may decrease the severity of cardiovascular disease in the elderly.\textsuperscript{159} Thus, the lack of endogenous activation of this redox sensitive transcription factor does not support an upregulation in cytoprotective ROS signaling in the aged heart.

MPTP Opening in the Aged Heart: Relationship With ROS Production

The susceptibility to MPTP opening is increased in the aged heart,\textsuperscript{101} increasing the potential of augmenting disease-enhanced permeability transition. Although the precise identity of the permeability transition pore remains a matter of debate, emerging data support complex V as a key component,\textsuperscript{190} and contributions of the phosphate carrier\textsuperscript{190} and contact sites\textsuperscript{161} still deserve consideration (Figure 6).

In contrast to the severe metabolic stress of ischemia–reperfusion with attendant cardiac overload and oxidative storm, the role of enhanced permeability transition pore opening in the aged heart during baseline metabolism is possibly related to reversible transient opening (flickering) of the pore. This may participate in the regulation of mitochondrial calcium content\textsuperscript{162} and can affect membrane potential. Calcium overload in the mitochondria does not seem to be a primary mechanism of pore opening during basal metabolism although transient calcium release from sarcoplasmic reticulum via mitochondria-associated membranes, especially in response to mitochondrial driven oxidant production as discussed above, deserves consideration. A well-known stimulus for pore opening is oxidative stress,\textsuperscript{163} especially that from the ETC. ROS production from complex I\textsuperscript{164} and possibly complex III\textsuperscript{165} favors pore opening in line with the sites of its production in the aged heart. Furthermore, blockade of the ETC proximal to complex III decreases the likelihood of pore opening.\textsuperscript{166} Thus, increased susceptibility to pore opening is a potential effector of ETC-mediated enhanced ROS production.

Mitochondrial Metabolism–Based Signaling in Response to ROS Production

Mitochondria serve as important signaling nodes for cell survival and death. In addition to serving as stochastic sources of ROS production, mitochondrial homeostasis is important
for cell survival and death. Oxidant-mediated damage to proteins within mitochondria leads to activation of new reinforcing signaling in response to cell stress. The potential of ETC-mediated mitochondrial oxidative damage increasing the susceptibility to permeability transition pore opening was discussed above. Signaling-mediated readouts of mitochondrial metabolism and oxidant production are critical to cardiomyocyte survival in the aged heart. Enhanced ROS production from IFM may indeed drive regional redox signaling. The combination of increased ROS production with relative blockade at cytochrome oxidase would support the preferential activation of the cytochrome c cardiolipin peroxidase in IFM from aged hearts.

Cytochrome c, a carrier component of the ETC, can undergo oxidative modification and activate oxidant-dependent signaling for cell death. It contains binding sites for cardiolipin.62 In the normal state, all the coordination positions of the heme iron are occupied. The heme iron has 2 axial ligands, His18 and Met80. Oxidation of Met80 to methionine sulfoxide opens the axial coordination site, allowing acquisition of a peroxidase function of electron transfer from H2O2 to cardiolipin.167 The peroxidation and depletion of cardiolipin signal the activation of cell death programs. 58 An increase in intramitochondrial ROS generation coupled with the electron flow through the cytochrome c segment of the ETC oxidizes cytochrome c, resulting in depletion of cardiolipin.51 The oxidative stress of ischemia–reperfusion increases cytochrome c methionine sulfoxide, indicative of peroxidase formation in the in situ heart.61 The role of cytochrome c peroxidase formation in the cardiolipin alterations that occur with aging requires further study.

The activation of oxidant-sensing signaling systems for cell survival includes the redox-sensitive protein kinase ASK-1. ASK-1 is present in an inactive complex with the reduced form of thioredoxin. When oxidative stress is increased, ASK-1 dissociates from thioredoxin, resulting in ASK-1 activation.168 ASK-1 activates the mitogen-activated protein kinase cascade. In the liver, aging leads to activation of ASK-1 in the baseline state.169 In response to stress, there is evidence in brain of age-enhanced activation of ASK-1.170 ASK-1 is a mediator of cell death in the heart in response to ischemia–reperfusion,171 but its role in the aging heart in response to baseline stress remains uncertain. ASK-1 activation in response to oxidative stress can affect OXPHOS and susceptibility to permeability transition.172 Thus, oxidant production from mitochondria might activate ASK-1, which interacts with cardiac stress responses171 and potentially further alters mitochondrial function.

**Regulation of Mitochondrial Metabolism by Transcription Factors**

The ability to acutely regulate oxidative metabolism concomitant with a redirection of transcriptional programs is an appealing mechanism for a concerted cell stress response, especially for aging tissues susceptible to age-enhanced disease.
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Transcription factors have been identified within mitochondria. Some transcriptional factors localize to the outer membrane and regulate outer membrane permeability and susceptibility to cell death. Modulation of mtDNA expression by nuclear transcription factors is an elegant expression of mitochondria–nucleus crosstalk and likely contributes to the regulation and stability of mtDNA as discussed above. Regulation of mtDNA can affect metabolism via regulation of mtDNA-encoded catalytic subunits of complexes I, III, IV, and V. A more direct modulation of ETC activity and OXPHOS is evident for STAT3 and perhaps for p53. These latter 2 peptides are incorporated into mitochondria.

STAT3 provides a central contribution to stress response with a cardioprotective role. In addition to its canonical actions as a transcription factor, a pool of STAT3 resides within the mitochondria in the matrix of both SSM and IFM. STAT3 binds to GRIM-19 (gene associated with retinoic-interferon-induced mortality 19), a subunit of complex I. Mitochondria-localized STAT3 modulates the activity of the ETC although it is clearly not present in a 1:1 stoichiometry with metabolic targets. The role of STAT3-mediated STAT3 provides a central contribution to stress response in the mitochondria in the matrix of both SSM and IFM. STAT3 deletion and inhibition of mitochondria are more sensitive to calcium-induced opening of the MPTP, likely reflecting the association of STAT3 with cyclophilin D. The role of STAT3-mediated processes in relation to age-related OXPHOS defects and the response to exogenous stress of mitochondria from aged hearts remain areas of active investigation.

Stress-induced translocation of p53 to the mitochondria involves monoubiquitination of a distinct cytoplasmic pool of p53 by the E3 ligase MDM2 (mouse double minute 2 homolog). The translocation of p53 to the outer membrane modulates members of the bcl-2 family and affects susceptibility to programmed cell death. p53 also accesses the matrix compartment. p53 is activated in senescent tissues, including endothelial cells, and thus may affect vascular function and perhaps even metabolism in the aged heart.

Mitochondrial Fission and Fusion

Many excellent reviews have highlighted the importance of fission and fusion processes in cardiac injury during ischemia–reperfusion and subsequent heart failure development. Mitochondrial dynamic processes are proposed to be involved in the aging process. The blockade of fission or promotion of fusion contributes to cell senescence. Knockout of mitochondrial fission protein 1 (Fis1) in cultured cells results in elongation of mitochondria accompanied by cell morphological changes of senescence, including enlargement and flattening, as well as staining for senescence-associated acidic β-galactosidase activity and increased expression of mitofusin-1. Cell senescence is observed in dysfunctional endothelial cells during aging. However, the effect for cardiac myocytes, which do not exhibit a classic senescent transcriptional program, including β-galactosidase activity, is less clear. Nonetheless, this body of work supports the notion that enhanced mitochondrial fission may attenuate age-induced cellular dysfunction, likely via isolation and removal of dysfunctional mitochondria as discussed below. In fact, fission-associated autophagy is emerging as an important mechanism of mitochondrial homeostasis in the heart.

Post-translational modification of mitofusin-1 modulates cell responses during oxidative stress. In antimycin A–treated cells, the mitofusin-1 level is markedly increased with augmented cell death. Antimycin-A is a complex III inhibitor that is used to increase ROS production from the Qo site of complex III, favoring ROS production in a similar manner to the age-related defect discussed above. Proper regulation of mitofusin-1 content leading to a balance of mitochondrial fission and fusion needs to be maintained to promote cell survival during oxidative stress. Mitofusin ubiquitination is increased in antimycin-A–treated cells, leading to proteasome degradation and decreased fusion in response to oxidative stress. Inhibition of mitofusin-1 degradation increases cell death in antimycin-A–treated cells. These studies indicate a net protective role of mitochondrial fission in cell senescence and aging.

The content of mitofusin-1 and mitofusin-2 is increased in skeletal muscle in aged mice, whereas the Fis1 level is decreased. Beclin 1 content is also decreased. These results suggest that aging increases mitochondrial fusion and attenuates mitophagy. The findings in skeletal muscle again support the concept that fusion favors protection against oxidative stress. Manipulation of mitochondrial dynamics is a new strategy to decrease cardiac injury during ischemia–reperfusion. Thus, the enhanced oxidant production present in the aged heart may impair protective mitochondrial fission–based responses to superimposed disease. Modulation of mitochondrial dynamic changes may be a strategy to attenuate the deleterious effect of age-related defects in the ETC. Decreased fission in the baseline state may predispose to an increased susceptibility of the aged heart to injury.

Mitochondrial Biogenesis, Dynamics, and Removal

Age-related decreases in mitochondrial yield and OXPHOS are limited to IFM. The decrease in IFM may reflect a population with content decreased because of the impaired production or a more rapid turnover because of increased removal. Mitochondrial biogenesis and removal are altered by age. In contrast to the neonatal heart, the activation of PGC1-α (peroxisome proliferator-activated receptor gamma coactivator 1 alpha)–mediated mitochondrial biogenesis in the adult heart did not lead to evident region-specific proliferation within the myocyte. The differential responses in adult and neonatal hearts to activation of a constitutively active PGC1-α transgene might be related to the pre-existing developed cardiomyocyte cellular architecture in the adult. Targeted removal of IFM may be enhanced in the aged heart. The defective IFM, with increased ROS production and potential for membrane depolarization attributable to enhanced susceptibility to permeability transition, should be targeted for elimination by mitophagy. Such removal would attenuate the oxidative-driven injury mechanisms discussed above. Membrane depolarization may activate...
Parkin-mediated mitophagy, or, alternatively, appropriate activation of fission may activate fission-driven autophagy. However, the localization of age-related defects to IFM suggests that because of their siting among the myofibrils, removal of these mitochondria may be impaired. In this case, reduced removal would point to decreased mitochondrial biogenesis as the mechanism of the decreased content of IFM with age. In fact, rates of replacement and half-lives of the 2 populations in vivo is a key question relevant to the aged heart and can be addressed by stable isotope approaches and the analysis of mitochondrial proteins and phospholipids. It is critical to understand the activation of mitochondrial removal mechanisms in vivo in the aged wild-type heart, both at baseline and in disease states. Transgenic models provide key insights into mechanisms of removal but may be less informative in identifying the pathway of activation for removal of dysfunctional mitochondria in aging with or without superimposed disease. An impaired response of mitophagy could contribute to the increased susceptibility of the aged heart to cardiac stress, and impaired biogenesis of mitochondria could enhance susceptibility of the aged heart to superimposed stress.

Proteolytic enzyme–mediated protein degradation affects cardiovascular dysfunction in acquired heart disease. An increase of Omi/HtrA2 (an intermembrane space protease) content enhances cardiac injury in aged hearts compared with adult hearts. In contrast, loss of Omi/HtrA2 causes premature aging. In aged rat hearts, Lon protease activity is decreased even despite an increase in protein content. However, the downregulation of Lon can decrease cell injury during hypoxia–reoxygenation. The decreased Lon activity may contribute to suppressed autophagy during aging.

Harnessing the Mitochondria: Treatment of Age-Enhanced Cardiac Disease by Modulation of Aging-Induced Defects

Mitochondria-directed strategies to limit cardiac injury are highly relevant to the protection of the aged heart and to the ultimate improvement of clinical outcomes in high-risk elderly patients. Relevant to mitochondrial metabolism in the aged heart and treatment of cardiac disease in elderly patients is the goal to modulate or mitigate age-related defects in mitochondrial metabolism to reduce injury from subsequent cardiac disease. Novel therapies are required because classical approaches widely used in experimental studies in the adult heart are of limited benefit when applied to the aged heart. Activation of cytoprotective signaling cascades that center on mitochondria in ischemic preconditioning and postconditioning is clearly less effective in the aged heart. It remains unclear if the ineffectiveness of signaling-based cytoprotection in the aged heart is at the level of the signaling cascades upstream of the mitochondria or the inability of dysfunctional mitochondria to respond to the cytoprotective modulation. It seems that mitochondria in the aged heart retain the capacity to respond to cytoprotective modulation because endogenous protective mechanisms can be restored in aging hearts by treatments, including caloric restriction (CR) and exercise.

Compared with young rats, the rate of oxidation is decreased in permeabilized cardiac fibers isolated from aged rat hearts using pyruvate/malate and succinate as complex I and complex II substrates. CR improves OXPHOS with complex I but not complex II substrates. CR also improves complex I activity in aged hearts through induction of ND6 expression (a complex I subunit encoded by mtDNA). CR does not affect ETC enzyme activity nor mitochondrial respiration in young rats. CR can improve mitochondrial biogenesis through reduction of oxidative stress and activation of sirtuins. Resveratrol supplementation also provides benefit in delaying aging-mediated cardiovascular dysfunction. CR, exercise, and resveratrol all activate sirtuin-1 and 3. The details can be found in many excellent reviews.

In Fisher 344 rats, wheel running exercise decreases mitochondrial production of H$_2$O$_2$ with reduced MnSOD activity in both SSM and IFM from aged rat hearts. However, acute prolonged exercise paradoxically may impair OXPHOS and lead to decreased respiratory coupling. Thus, proper exercise may provide a beneficial effect in improvement of mitochondrial oxidative metabolism.

Furthermore, isolated mitochondria from aged hearts respond to pharmacological effectors, including direct agonists of the mitochondrial potassium-ATP channel. Thus, the potential for direct mitochondria-targeted intervention remains. The aged heart exhibits a major clinical challenge for protective therapy. First, not only myocardial injury increases compared with younger hearts for similar ischemic stress but also the ability to muster endogenous protective pathways is impaired. This challenge in the aged heart makes a strong case for the consideration of novel, direct mitochondrial-centered treatments to mitigate cardiac damage during acute and chronic cardiac stress.

If the aging defect in mitochondrial respiration could be diminished or removed, would the aged heart now sustain less injury? Acetylcarnitine treatment improved aging-induced decreases in OXPHOS, complex III and complex IV. The content of cytochrome b in IFM from aged hearts was increased. In the aged heart, acetylcarnitine treatment improved tolerance to ischemia–reperfusion injury to that observed in adult controls, with decreased infarction and improved contractile recovery. Acetylcarnitine increased the transcription of mtDNA linked to a greater content of ETC subunits, indicating stimulation of mitochondrial protein synthesis. Increased transcriptional responses may occur via activation of mitochondrial sirtuins, or alternatively, via increases in intracellular acetyl-CoA. The latter may activate nuclear transcription via modulation of nuclear epigenetic responses. The acetylcarnitine studies provide proof of concept that modulation of aging-induced defects in mitochondrial metabolism can reduce cardiac injury from cardiac disease. The approach to rejuvenate mitochondrial function to directly address age-enhanced cardiac disease remains an attractive and potentially useful clinical strategy.

In addition to the defect in the ETC of the aged hearts, post-translational modification can also contribute to the altered mitochondrial metabolism. Sirtuins can affect mitochondrial metabolism through reversible lysine-residue acetylation. In female Wistar rats, the activities of complexes I–IV are decreased in middle and aged hearts compared with young rats. The NAD$^+$ content in middle and aged hearts...
is decreased compared with young hearts, whereas NADH content is increased in middle and aged hearts. Thus, the altered sirtuins may contribute to altered metabolism in aged hearts. As an alternative, therapy to directly increase NAD+ content remains an option, having been used in skeletal muscle and brain, but the effect on heart remains to be seen.

Supplemental coenzyme Q10 in polyunsaturated fatty acid diet extends life span in 24-month-old rats with decreased H2O2 generation and increased catalase activity. The coenzyme Q10 supplementation in polyunsaturated fatty acid diet also improves the activity of cytochrome oxidase in 24-month-old mouse heart mitochondria. However, addition of coenzyme Q10 does not affect the respiratory chain activities, superoxide generation, and antioxidants in C57BL/6 mice. Coenzyme Q10 may attenuate the aging defect in heart mitochondria.

Rapamycin is known to extend life span in animal species. Feeding of rapamycin in late life extends life span in C57BL/6 mice with decreased metabolite rate. In aged female C57BL/6 mice, rapamycin feeding for 10 weeks transiently induces autophagy, increases mitochondrial biogenesis, improves energy metabolism, especially fatty acid metabolism, and alters the myocardial metabolome.

Rapamycin therapy started even late in life exerted beneficial effects in cardiac function and cardiac gene and protein expression. The response to superimposed stress of ischemia–reperfusion or heart failure remains an area of major interest.

Summary and Conclusions

Aging results in defects in cardiac mitochondrial metabolism centered on the ETC. IFM, located among the myofibrils, sustains the greatest alteration with age, exhibiting a decrease in both number and mass and a depressed capacity for OXPHOS because of defects in ETC complexes III and IV. The presence of dysfunctional mitochondria reflects age-induced alterations in mitochondrial dynamics involving altered mitochondrial fission and fusion. Age-altered mitochondria produce greater fluxes of ROS, leading to damage of mitochondrial components, injury to adjacent organelles, and finally and fatally to the oxidant activation of signaling pathways for cell death. Reduced electron transport may, in part, be because of age-related dysregulation of transcription factors that regulate mitochondrial metabolism, an understudied area. Impaired metabolism of fatty acids, dysregulated glucose metabolism, and mitochondrial defects are critical in metabolic responses of the elderly heart to disease-imposed stress. Aging defects in mitochondria represent new therapeutic targets, whether by manipulation of the mitochondrial proteome, modulation of electron transport, activation of biogenesis or mitophagy, or the regulation of fission and fusion. The study of aging defects in cardiac metabolism is not a sterile one, rather an area that presents an opportunity for developing novel therapies that could benefit cardiac disease and perhaps slow the pace of age-induced changes in the heart, with the happy result of lengthening life spans.

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Disclosures

None.

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Edward J. Lesnefsky, Qun Chen and Charles L. Hoppel

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