Mitochondria functionality and sperm quality

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Abstract

Although mitochondria are best known for being the eukaryotic cell powerhouses, these organelles participate in various cellular functions besides ATP production, such as calcium homeostasis, generation of reactive oxygen species (ROS), the intrinsic apoptotic pathway and steroid hormone biosynthesis. The aim of this review was to discuss the putative roles of mitochondria in mammalian sperm function and how they may relate to sperm quality and fertilisation ability, particularly in humans. Although paternal mitochondria are degraded inside the zygote, sperm mitochondrial functionality seems to be critical for fertilisation. Indeed, changes in mitochondrial integrity/functionality, namely defects in mitochondrial ultrastructure or in the mitochondrial genome, transcriptome or proteome, as well as low mitochondrial membrane potential or altered oxygen consumption, have been correlated with loss of sperm function (particularly with decreased motility). Results from genetically engineered mouse models also confirmed this trend. On the other hand, increasing evidence suggests that mitochondria derived ATP is not crucial for sperm motility and that glycolysis may be the main ATP supplier for this particular aspect of sperm function. However, there are contradictory data in the literature regarding sperm bioenergetics. The relevance of sperm mitochondria may thus be associated with their role in other physiological features, particularly with the production of ROS, which in controlled levels are needed for proper sperm function. Sperm mitochondria may also serve as intracellular Ca2+ stores, although their role in signalling is still unclear.

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The mitochondrion: a multidimensional organelle

Mitochondria are important and unique organelles, and ongoing research keeps highlighting novel ways in which they participate in cellular functions. One main characteristic that separates the mitochondrion from other organelles is the presence of its own circular genome, mitochondrial DNA (mtDNA) and specific ribosomes, thus allowing for local protein synthesis (St John et al. 2010). Although mtDNA only codes for 13 mitochondrial proteins (Fig. 1), their expression might be essential for mitochondrial function. To this extent, mtDNA defects have been associated with a range of human disorders (including neurodegenerative diseases and cancer), as well as with ageing (for recent reviews, see Greaves et al. (2012) and Schon et al. (2012)). The development of animal models harbouring mtDNA mutations corroborated this association and contributed to the elucidation of mitochondrial disease mechanisms (Dunn et al. 2012).

In addition, mitochondria feature four defined interconnected compartments: the outer mitochondrial membrane (OMM) and inner mitochondrial membrane (IMM), the intermembrane space and the mitochondrial matrix (Fig. 1). The similarities between the IMM and the cellular membrane of prokaryotic organisms (including the presence of the lipid cardiolipin), together with the existence of mtDNA, stress the possibility that mitochondria were once symbionts inside the cell, which progressively lost autonomy as most of their genome migrated to the nucleus, resulting in a full integration and control of mitochondria in eukaryotes (Alberts et al. 2008).

The IMM is usually convoluted, presenting several invaginations (cristae) but, unlike what is often assumed, this general arrangement is very variable, and the number, structure and extension of IMM cristae may have functional consequences (Bereiter-Hahn & Jendrach 2010). Furthermore, mitochondrial morphology itself is also plastic, with components of specific mitochondrial fission and fusion machineries promoting reversible changes from ovoid mitochondria to extensive interconnected filamentous organelles (Campello & Scorrano 2010). Finally, the functional importance of
mitochondrial connections to other organelles (such as the endoplasmic reticulum) and the cytoskeleton is gaining attention, as it may help to integrate distinct cellular functions (Anesti & Scorrano 2006, Rowland & Voeltz 2012).

Mitochondria participate in many crucial processes in eukaryotic cells, the better known of which is the production of ATP via oxidative phosphorylation (OXPHOS), which is preceded by the generation of reduced electron carriers, both in the cytoplasm (via glycolysis) and in the mitochondrial matrix (where the Krebs cycle and the oxidation of most fatty acids take place, Fig. 2). The IMM includes several complexes that make up the electron transfer chain (ETC, Fig. 1A), which transports electrons obtained from the oxidation of NADH and the FADH2 moiety of succinate dehydrogenase, ultimately reducing the final acceptor oxygen to water. In this process, a quimio-osmotic proton gradient is generated across the IMM and is subsequently used by the ATP synthase to phosphorylate ADP to ATP. The proton gradient has two components, a minor chemical (pH) component and a major electric component, which is usually translated into the mitochondrial membrane potential (MMP). The electric nature of the MMP (with a negatively charged mitochondrial matrix) can also be harnessed to sequester calcium ions and thus participate in calcium homeostasis (Nichols & Ferguson 2002).

**Figure 1** The mitochondrial electron transfer chain (ETC) and the production of ATP by oxidative phosphorylation. (A) The structure, composition and localisation of the ETC complexes is represented. Examples of inhibitors of each of the complexes are also indicated. (B) Proteins constituting each of the complexes. Adapted from the KEGG Pathway Database (http://www.genome.jp/kegg/pathway.html; Kanehisa et al. 2012). Details: pink rectangles, proteins described in human sperm proteomic studies (Amaral et al. 2013); green rectangles, proteins likely to be present but that have not been detected in human sperm proteomic projects; white rectangles, prokaryotic proteins; rectangles with blue frame, proteins encoded by the mitochondrial genome (all the others are nuclear encoded).
Besides its involvement in ATP synthesis, the mitochondrial ETC promotes the production of reactive oxygen species (ROS), which can both function in signalling pathways and cause oxidative damage, if produced in an unchecked manner. Remarkably, the mobile ETC carrier cytochrome c moonlights as an active participant in the mitochondria-mediated intrinsic apoptotic pathway. In fact, one of the hallmark triggers of this process is cytochrome c release into the cytoplasm.

Importantly, for reproductive biology, mitochondria are also the starting point for steroid hormone biosynthesis (Ramalho-Santos & Amaral 2013). Indeed, the conversion of cholesterol to pregnenolone (a common precursor for all steroid hormones) is catalysed by the cytochrome P450 side-chain cleavage enzyme (P450scc) on the IMM (Stocco & McPhaul 2006). Moreover, mitochondrial ATP synthesis seems to be required for steroid biosynthesis in Leydig cells (Midzak et al. 2011). More recently, mitochondria and mitochondrial processes have been identified as participating in many other events, stressing its role in the integration of metabolism, cell signalling, cell proliferation, epigenetic regulation, cell cycle control, cell differentiation and cell death (Nunnari & Suomalainen 2012). Throughout this article, we will touch on several aspects of
mitochondrial functionality, specifically as they pertain to sperm function, and notably to human sperm, with brief mentions of research carried out in other species, as appropriate.

**Sperm mitochondria**

Germ cell mitochondria change throughout spermatogenesis: while spermatogonia and early spermatocytes harbour orthodox mitochondria, late spermatocytes, spermatids and sperm have more condensed (and metabolically more efficient) forms (see Ramalho-Santos et al. 2009). Additionally, concurrent to the loss of the majority of the cytoplasm occurring during spermiogenesis (the differentiation of spermatids into sperm), some mitochondria are lost in residual bodies. The 22–75 remaining mitochondria rearrange in tubular structures that are helically anchored around the anterior portion of the nine outer dense fibres (ODFs) and of the axoneme, constituting the midpiece (Otani et al. 1988, Ho & Wey 2007; Fig. 3). The anchorage of the mitochondrial sheath is sustained by a complex of filaments called sub-mitochondrial reticulum (Olson & Winfrey 1990) and seems to depend on the expression of kinesin light chain 3 (KLC3), a protein that may bind both ODF1 and a mitochondrial outer membrane porin, creating a bridge between them. Indeed, transgenic male mice expressing a KLC3 mutant protein that cannot bind ODF1 have abnormal sperm midpiece formation, low sperm quality and reduced fertility (Zhang et al. 2012). On the other hand, the sperm OMMs are covered by a keratinous structure formed by disulphide bonds between cysteine- and proline-rich selenoproteins (Ursini et al. 1999). This structure, the so-called mitochondrial capsule, may confer protection to sperm mitochondria (and mtDNA) and certainly contributes to the impracticability of fully isolating these organelles. Logically, the number of mitochondrial proteins and of mtDNA molecules per cell is also reduced during spermiogenesis (Hecht et al. 1984, Larsson et al. 1997). However, given that most of the cytoplasm is lost during this differentiation process (thus greatly reducing cell volume), this may be paralleled by an increase in mtDNA copy number per volume unit (Diez-Sanchez et al. 2003).

Interestingly, sperm from a few non-mammalian animal species that live in habitats with very low oxygen levels lack mitochondria (Balsamo et al. 2007), suggesting that nature has a way of getting rid of needless mitochondria during spermiogenesis. On the contrary, mammalian sperm preserves a number of mitochondria in a specific subcellular compartment, indicating that the functionality of these organelles might be crucial. In addition, and at least in rodent species, it seems that sperm mitochondria become polarised, and thus functional, after epididymal maturation (without which sperm is unable to achieve in vivo fertilisation; Aitken et al. (2007)). Likewise, a remarkable change in human sperm mitochondria towards a more loosely wrapped morphology, possibly resulting from an increase in mitochondrial volume, was associated with capacitation (a second maturation process usually occurring in the female reproductive tract and without which in vivo fertilisation is not possible; Vorup-Jensen et al. (1999)). These observations suggest that active sperm mitochondria are required for fertilisation. From an evolutionary point of view, having more mitochondria may be advantageous, as sperm from primate species with multiple partners (and thus with stronger sperm competition) have a greater midpiece volume than sperm from monogamous species (Anderson & Dixson 2002).

Nevertheless, it is important to note that, although mitochondria are present in the male gamete, paternal mtDNA is generally not transmitted to the embryo in mammalian intraspecific crosses. However, despite what is depicted in many scientific textbooks, the reason for this paternal-only mtDNA transmission is not that the sperm tail is discarded outside the oocyte at fertilisation but rather that paternal mitochondria are degraded inside the zygote, following penetration of the entire male gamete into the oocyte (Ramalho-Santos 2011).
Having said this, the time frame during which sperm mitochondria functionality is physiologically relevant and needs to be maintained comprises the period between epididymal storage, ejaculation, travelling between the female reproductive tract and sperm–oocyte interactions. Any alteration in the mitochondrial genome, transcriptome, proteome or metabolome, or any cellular event resulting in compromised sperm mitochondrial functionality during this time may potentially affect sperm function, as will be discussed in detail (Table 1).

Mitochondrial functionality and sperm quality

First of all, defects in sperm mitochondrial ultrastructure seem to associate with decreased sperm motility in humans (Mundy et al. 1995, Pelliccione et al. 2011). At the molecular level, previous work has shown that deletions and other changes to mtDNA that influence cellular homoeostasis can result in reduced sperm functionality and male infertility, both in human patients (for review see St John et al. 2005) and in mice engineered to harbour a mutant mtDNA with a pathogenic 4696-bp deletion (Nakada et al. 2006). Likewise, microarray analysis suggested that sperm from asthenozoospermic samples have altered levels of specific mtRNAs, as well as of nuclear-encoded transcripts encoding mitochondrial proteins (Jodar et al. 2012). However, and at least for some mtRNAs, this putative difference could not be corroborated by quantitative real-time PCR. Moving beyond the mitochondrial genome/transcriptome, the expression of mitochondrial proteins, and notably ETC subunits, is associated with sperm quality (Amaral et al. 2007). In fact, comparative proteomic outcomes suggest that the expression of several sperm mitochondrial proteins may be altered in asthenozoospermic patients (Zhao et al. 2007, Martinez-Heredia et al. 2008, Chan et al. 2009, Siva et al. 2010, Parte et al. 2012). Furthermore, the activity of sperm mitochondrial enzymes, including ETC complexes, also correlates with sperm parameters, including concentration, vitality and motility (Ruiz-Pesini et al. 1998, 2000a), although it should be noted that the highest correlations found were for the activities of citrate synthase and ETC Complex II (succinate dehydrogenase), which are nuclear-encoded proteins that are part of the Krebs cycle. In addition, the normalisation of other activities to citrate synthase (often used as a marker for mitochondrial content) suggested that the main explanation for these correlations might be mitochondrial volume, not distinct enzymatic activities in samples of varying quality (Ruiz-Pesini et al. 1998). Additionally, mice lacking the testis-specific form of cytochrome c also have impaired sperm function (Narisawa et al. 2002). Furthermore, oxygen consumption in sperm mitochondria and mitochondrial respiratory efficiency also correlate with motility (Stendardi et al. 2011, Ferramosca et al. 2012), and many different ETC inhibitors (Fig. 1) have been shown to negatively affect sperm motility (Ruiz-Pesini et al. 2000b, St John et al. 2005). Given that these results depend on an organized ETC (rather than on the activity of individual components), the data suggest that a functional organelle is important for sperm function. In accordance with this notion, the same should be valid for mitochondrial parameters that depend on intact mitochondria, namely the MMP.

Indeed, and although accurately monitoring MMP in sperm may be challenging (Amaral & Ramalho-Santos 2010), this parameter clearly correlates with functional sperm parameters, including motility (Troiano et al. 1998, Marchetti et al. 2002, 2004, Gallon et al. 2006, Paoli et al. 2011, Wang et al. 2012), and with fertilisation ability, monitored both in model systems (Sousa et al. 2011) and in patients undergoing assisted reproduction (Kasai et al. 2002, Marchetti et al. 2012). Interestingly, recent data suggest that the sperm motility of patients with abnormal sperm parameters can be enhanced by incubation with myoinositol, and this seems to be paralleled by an increase in the proportion of sperm with high MMP (Condorelli et al. 2012).

Finally, mitochondrial functionality may also be required for sperm capacitation. To this extent, a peak in oxygen consumption was observed during in vitro capacitation and progesterone-induced acrosome reaction in bovine and boar sperm (Cordoba et al. 2006, Ramio-Lluch et al. 2011). In addition, it is well established that several sperm mitochondrial proteins undergo capacitation-dependent tyrosine phosphorylation (for a review, see Shiavi et al. (2009)).

The preceding paragraphs seemingly stress that mitochondrial functionality is important for sperm activity, or, at the very least, that functional mitochondria help define a functional male gamete (Table 1). But what is exactly the role of mitochondria in sperm? Given that mitochondria are crucial for ATP production in eukaryotic cells and that ATP, in turn, is needed for sperm motility, the obvious answer would be to link these two events. However, the emerging portrait is much more complex, as will be discussed in the following section.

Sperm metabolism: not a linear story

In fact, the issue of sperm metabolism related to motility is the subject of an extensive debate (Ramalho-Santos et al. 2009), and some compelling evidence suggests that mitochondria-derived ATP is not paramount for motility, but rather that glycolysis may be the main ATP provider in this case, with mitochondrial activity at this level possibly related to other aspects. This hypothesis was first discussed in terms of compartmentalisation, namely that ATP produced in the midpiece would take too long to diffuse (or shuttle) along the flagellum, notably in species with longer sperm tails, such as rodents, although this
Others
Mitochondrial mice models

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Table 1 Experimental evidence suggesting an association between mitochondrial functionality and sperm quality.

notion is disputed (Ford 2006). There are, however, several lines of evidence that seem to favour glycolysis as the main ATP source for sperm movement. These include, for example, the need for glucose to maintain sperm function, a need that cannot be replaced with OXPHOS substrates (Peterson & Freund 1970, Williams & Ford 2001, Amaral et al. 2011, Hereng et al. 2011). Furthermore, male mouse knock-out models for the glycolysis-associated enzymes enolase 4 (Nakamura et al. 2013), phosphoglycerate kinase 2...
(Danshina et al. 2010), lactate dehydrogenase-C4
(LDHC; Odet et al. 2008) and glyceraldehyde
3-phosphate dehydrogenase-S (Miki et al. 2004) have
impaired sperm function (notably in terms of motility)
and suffer fertility loss, with the latter model maintaining
normal mitochondrial activity. However, recent data
have shown that, at least for LDHC, the severity of the
results depends on the mouse strain, with some strains
relying more on glycolysis than others (Odet et al. 2013).
Using laser tweezers, it was also shown that human
sperm motility was not dependent on MMP (Nascimento
et al. 2008).

Therefore, it seems clear that there are contradictory
data in the literature and that other metabolic pathways
may be involved in sperm motility. Recent data suggest
that the use of endogenous substrates, including the
oxidation of fatty acids (Fig. 2), may be important for this
process (Amaral et al. 2013), which should also be
dependent on what physiological substrates and conditions the sperm encounters in vivo (Storey 2008).

**Other aspects of mitochondrial physiology and sperm quality**

**ROS production**

Sperm can be affected by ROS produced locally, or by
ROS formed in leucocytes present in semen (Whittington
& Ford 1999). Mitochondria are the main source of
sperm-produced ROS, notably via the formation of superoxide in the ETC, although NADPH oxidase may
also be an additional source (Koppers et al. 2008, Kothari
et al. 2010). Importantly, controlled ROS levels are
needed for proper sperm function (notably for motility,
capacitation, the acrosome reaction, hyperactivation
and fertilising ability), while ROS can also have a
pathological effect on the male gamete, if in excess, or if
there is an imbalance with available antioxidant
defences, resulting in a decrease in viability, motility,
MMP, and increases in DNA damage, morphology
defects and lipid peroxidation, possibly resulting in
apoptosis-like phenomena, as will be discussed below
(Kothari et al. 2010, Mahfouz et al. 2010, Aitken et al.
2012b). The recent development of specific probes for
mitochondria-produced ROS (mROS) shows that exces-
sive production results in membrane peroxidation and
Additionally, a higher content of unsaturated fatty acid
on sperm is also related to an increase in mROS again
leading to motility loss and DNA damage (Koppers et al.
2010). Interestingly, mROS levels seem to vary in
ejaculates, and when sperm are separated by Percoll
gradients, the low-density fraction has a more prominent
number of positive cells for mROS than the high-density
fraction (Koppers et al. 2008, Aitken et al. 2013). These
results have suggested that both enzymatic and non-
enzymatic antioxidants could be used to control the
damage caused by excessive ROS levels in sperm, and
there is some evidence that seems to substantiate this
hypothesis, interestingly with antioxidants that specifi-
cally target mitochondria (Lamond et al. 2003, Aitken
et al. 2012a).

**Apoptosis**

Although the capacity of mature sperm to carry out
apoptosis has been questioned due to the paucity of
cytoplasm, it is well known that human sperm can
possess apoptotic markers and that this may influence
sperm function and perhaps be involved in the removal of
DNA-damaged sperm in the female reproductive tract
(Ramalho-Santos et al. 2009, Aitken & Koppers 2011),
or, alternatively, result from leftover apoptotic phenom-
ena in the testis, possibly related to cases of male
infertility (Almeida et al. 2013). It is worth mentioning
that some studies note increases in sperm DNA damage
as evidence for apoptosis, but, while DNA damage is
certainly one of the main consequences of apoptosis,
apoptosis may not be the only possible mechanism
involved (Sousa et al. 2009, Aitken & De Iuliis 2010,
Sakkas & Alvarez 2010), and the notion of DNA damage
directly linked to a canonical apoptosis cascade in
sperm has been questioned (Koppers et al. 2011).

Although the extrinsic apoptotic pathway has been
suggested to be active in sperm (Sakkas et al. 1999),
we will focus on the intrinsic (mitochondria-dependent)
pathway, which involves, for example, both pro- and
anti-apoptotic members of the Bcl family and especially
on general apoptotic features, as there is clearly much
more information at that level. In terms of the intrinsic
pathway, anti-apoptotic Bcl-XL seems more prevalent in
ejaculated abnormal/immature sperm, possibly as a
spematogenesis remnant (Cayli et al. 2004), while the
presence of both pro- and anti-apoptotic forms of Bcl-x
have been proposed to exist in mature human sperm,
but no correlations with sperm parameters were shown
(Sakkas et al. 2002).

More general apoptosis hallmarks include the exter-
nalisation of phosphatidylserine (PS) to the outer leaflet
of the plasma membrane and caspase activation. PS
exposure can be monitored using fluorescent Annexin V
in unpermeabilised (live) cells. In fact, Annexin V
staining revealed more viable cells in normozoospermic
patients (Varum et al. 2007) and seemed to correlate
with sperm parameters in other studies (Shen et al. 2002,
Weng et al. 2002). Importantly, the use of magnetic
activated cell sorting (MACS) with Annexin V micro-
beads to select sperm reduced the percentage of altered
cells (Lee et al. 2010, Rawe et al. 2010, Tavalaee et al.
2012). On the other hand, the presence of activated
caspases (the final step in apoptosis) has also been
linked to poor sperm quality and lower fertilisation
potential, possibly by affecting sperm DNA (Weng et al.
Almeida et al. 2011), both in the case of caspase 9 (activated by the mitochondrial pathway of apoptosis following cytochrome c release) and caspase 3 (activated by both apoptotic pathways). Interestingly, caspase activity seems to be focused in the sperm midpiece (Weng et al. 2002, Paasch et al. 2004a), and the use of apoptotic inducers increases the activity of both caspases, lowering MMP and sperm motility (Paasch et al. 2004b, Grunewald et al. 2005, Espinoza et al. 2009, Kim et al. 2012). Recent studies have implicated mitochondrial ROS generation in human sperm apoptosis, with resulting ROS-derived DNA damage rather than DNA cleavage, thus linking both phenomena (Aitken et al. 2012c). An interconnection between capacitation and apoptosis signalling pathways has also been proposed (Grunewald et al. 2009).

**Ca^{2+} signalling**

Calcium signalling and calcium store mobilisation have recently been shown to be important in Assisted Reproductive Technologies (ART) success, as responses are clearly different when patients are compared with sperm donors (Alasmari et al. 2013). However, what role sperm mitochondria have in this process is open to question, although sperm mitochondria are known to uptake calcium, and have been hinted as a possible intracellular calcium store in human sperm (Costello et al. 2009). In somatic cells, mitochondrial calcium uptake is undertaken by a mitochondrial calcium uniporter (MCU; Fig. 2) and is known to control intracellular calcium signals, cell metabolism and cell survival (for recent reviews, see Rizzuto et al. (2012) and Patron et al. (2013)). Proteomic data have confirmed that human sperm do possess MCU, as well as MCU regulator 1 (Amaral et al. 2013, Wang et al. 2013). However, mitochondrial uncoupling does not seem to significantly affect the calcium oscillations occurring in either progesterone- or nitric oxide-stimulated human sperm (Harper et al. 2004, Machado-Oliveira et al. 2008). Likewise, during bull sperm motility hyperactivation, mitochondrial respiration does not appear to be up-regulated by the release of calcium to the axoneme (Ho & Suarez 2003). Taken together, these data suggest that direct roles of mitochondrial calcium uptake in the control of intracellular calcium signals or in cell metabolism in mammalian sperm are unlikely. Mitochondrial calcium signalling may be involved in the sperm intrinsic apoptotic pathway, but further studies are needed to better clarify this aspect.

**Conclusions and future perspectives**

Although mitochondria functionality seems to be crucial for mammalian sperm, and while functional mitochondrial parameters clearly correlate with human sperm functionality and fertilisation ability, its exact role in the male gamete is not completely clear (Fig. 2). At any rate, it seems that the specific and evolutionarily conserved mitochondrial concentration at the sperm midpiece of all mammalian species studied so far does not currently contribute towards centralising ATP production for sperm movement, as is often assumed in many Cell Biology textbooks (Alberts et al. 2008). Thus, the role of mitochondria in sperm function might be predominantly related to other physiological aspects. To this extent, on the one hand, the controlled production of mROS (balanced by effective antioxidant defences) seems to be required for sperm motility, capacitation and fertilising ability. On the other hand, the mitochondrial apoptotic pathway might prevent DNA-damaged sperm from participating in fertilisation and may also be linked to the removal of sperm from the female reproductive tract post-coitum (Aitken & Koppers 2011). Moreover, sperm mitochondria are putatively involved in Ca^{2+} homoeostasis, as these organelles may function as intracellular Ca^{2+} stores (Costello et al. 2009), but more studies are required to better understand this topic. Additionally, similar to what seems to happen in other cells (Lu & Thompson 2012), a crosstalk between mitochondrial metabolism and sperm epigenetics may exist. This is especially relevant given the recent finding that the sperm chromatin may transfer acquired epigenetic states across generations (Puri et al. 2010).

**Declaration of interest**

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the review.

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**Author contribution statement**

B Lourenço and M Marques contributed equally to this work.

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