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REVIEW ARTICLE

Deleterious effects of obesity upon the hormonal and molecular mechanisms controlling spermatogenesis and male fertility

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Abstract
Worldwide obesity rates have nearly doubled since 1980 and currently over 10% of the population is obese. In 2008, over 1.4 billion adults aged 20 years and older had a body mass index or BMI above a healthy weight and of these, over 200 million men and nearly 300 million women were obese. While obesity can have many ramifications upon adult life, one growing area of concern is that of reproductive capacity. Obesity affects male infertility by influencing the hypothalamic–pituitary–gonadal axis, thus causing detrimental effects upon spermatogenesis and subsequent fertility. In particular, evidence indicates that excess adipose tissue can alter the relative ratio of testosterone and oestrogen. Additional effects involve the homeostatic disruption of insulin, sex-hormone-binding-globulin, leptin and inhibin B, leading to diminished testosterone production and impairment to spermatogenesis. Aberrant spermatogenesis arising from obesity is associated with downstream changes in key semen parameters, defective sperm capacitation and binding, and deleterious effects on sperm chromatin structure. More recent investigations into trans-generational epigenetic inheritance further suggest that molecular changes in sperm that arise from obesity-related impaired spermatogenesis, such as modified sperm RNA levels, DNA methylation, protamination and histone acetylation, can impact upon the development of offspring. Here, we summarise our current understanding of how obesity exerts influence over spermatogenesis and subsequent fertility status, and make recommendations for future investigative research.

Keywords: *Obesity, spermatogenesis, body mass index, infertility, hypothalamic-pituitary-gonadal axis*

Introduction

In 2010, 48.5 million couples globally were affected by infertility (Mascarenhas et al., 2012). Specifically, infertility is estimated to affect one in seven couples in the Western world, with male factor infertility contributing to approximately 40% of these cases, female factor infertility to 45%, and the remaining proportion due to idiopathic causes (Fritz & Speroff, 2011). Interestingly, there has been a steady decline in fertility rates over the past 50 years, which has occurred in parallel with an increasing rate of obesity (Hammoud et al., 2012). Obesity is a medical condition where excess body fat has accumulated to an extent where it poses serious health risks, and is determined by body mass index (BMI), a measurement relating weight and height (Du Plessis et al., 2010). According to the National Institutes of Health, individuals with a BMI between 25 and 29.9 kg/m^2 are classified as 'overweight', while those with a BMI greater or equal to 30 kg/m^2 are classified as 'obese' (National Institutes of Health, 1998). Between 1980 and 2008, the worldwide prevalence of obesity nearly doubled, and more than 10% of the world's adult population is obese (Finucane et al., 2011).

While there has been substantial investigative research targeted to the impact of obesity upon female infertility, specific investigations of the exact relationship between obesity and male factor infertility are relatively rare and tend to be far less conclusive. One study reports that in patients seeking treatment for male infertility, there has been a three-fold increase in the prevalence of obesity (Kasturi et al., 2008). While current data remains highly conflicting, mounting evidence indicates that male obesity is associated with an increased time to conception, reduced pregnancy rates and an increase in pregnancy loss in couples undergoing assisted reproductive technology (ART) (Nguyen et al., 2007; Ramlau-Hansen et al., 2007; Hinz et al., 2010; Keltz et al., 2010; Bakos et al., 2011a).

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In order to produce healthy fertile sperm from testicular germ cells, the process of spermatogenesis must occur in a normal and natural manner. However, spermatogenesis is a highly complex and specialised process under strict regulatory mechanisms, which involve the hypothalamus, pituitary, Leydig cells, Sertoli cells and sex steroids (Ruwanpura et al., 2010). Large amounts of testosterone in the local vicinity, bound by androgen-binding protein in the seminiferous tubules, are required to maintain successful spermatogenesis. Normal luteinizing hormone (LH) secretion drives testosterone production by the interstitial Leydig cells, while normal follicle-stimulating hormone (FSH) secretion activates Sertoli cells to nourish developing sperm cells throughout the different phases of spermatogenesis. Fluctuations in this specialist environment, particularly with regard to temperature and hormones, have a strong impact upon the process of spermatogenesis. Any disorder affecting gonadotropin-releasing hormone (GnRH) secretion from the hypothalamus, or FSH and LH secretion from the pituitary, can impair spermatogenesis and thus fertility (Anawalt, 2013). While the most common cause of male infertility is the idiopathic failure of spermatogenesis, endocrinologists often encounter populations of men with treatable causes of sub-fertility, e.g. endocrinopathies such as obesity and hyperprolactinaemia (Anawalt, 2013).

This review explores how obesity in human males can result in hormonal imbalance with deleterious effects upon sperm formation, how impaired spermatogenesis can affect fertility status and how paternal obesity at the specific time of conception can influence subsequent health of the offspring.

Obesity can lead to deleterious alterations in important hormonal profiles

One of the most important roles of the hypothalamic–pituitary–gonadal (HPG) axis is in the regulation of reproductive function, and it is widely believed that obesity can lead to dysregulation of this vital physiological cascade. A bi-directional relationship has been established between hypogonadism and obesity (Rao et al., 2013), largely due to the complex interplay between hypothalamic hormones and the adipocytokines that control the pituitary–testicular axis. Endocrine changes associated with male obesity can thus result in conditions such as hypogonadotropic hyperoestrogenic hypoandrogenaemia, which may adversely affect fertility by reducing testicular function, modifying spermatogenesis or reducing sexual drive (Reis & Dias, 2012).

Aromatase over-activity can result in a reduced ratio of testosterone and oestrogen

Disruption of the HPG axis can result in reduced levels of testosterone and increased levels of oestrogen. These indications have long been associated with sub-fertility and are thus common markers of reproductive health (Handelsman & Swerdloff, 1985). The HPG axis governs the production of testosterone and is regulated via the direct negative feedback of testosterone upon the hypothalamus. The pulsatile release of GnRH by the hypothalamus drives LH secretion, which ultimately stimulates the testes to produce and secrete testosterone. In adipose tissue, testosterone is metabolised to oestradiol by the cytochrome P450 enzyme aromatase, which is responsible for a key step in the biosynthesis of oestrogens and is expressed in higher levels, and with increased activity, in white adipose tissue (DuPlessis et al., 2010). The increased bioavailability of aromatase in obese individuals results in the increased conversion of androgens to oestrogens, thereby simultaneously producing increased levels of circulating oestrogen. Increasing BMI has been shown to have a significant association with a reduced testosterone:oestrogen ratio (Hajshafiha et al., 2013).

Since oestrogen is more biologically active than testosterone and abnormally high levels of oestrogen can elicit negative feedback upon the HPG axis via kisspeptin neurons (Rao et al., 2013), the high levels of oestrogen in obese males consequently result in a reduction in testosterone production, subsequently affecting spermatogenesis (Schneider et al., 1979; Jensen et al., 2004; Hammoud et al., 2006; 2008; Roth et al., 2008; Chavarro et al., 2010; MacDonald et al., 2010). It has been hypothesised that kisspeptin secretion might be the central pathway linking obesity, testosterone deficiency and environmental factors (Figure 1). Oestrogens further act directly on the testes to regulate their function; different animal models exposed to high levels of oestrogenic chemicals showed a reduction in gonad size and a decrease in sperm count and quality in males (Akingbemi, 2005).

The only somatic cells directly in contact with developing male germ cells are Sertoli cells, which provide nutrients and support. The adhesion of Sertoli cells to the developing germ cells is dependent upon testosterone, with a reduction in testosterone leading to the retention and phagocytosis of mature spermatids (Kerr et al., 1993a,b). Furthermore, epithelial function in seminiferous tubules is disrupted by reduced intratesticular levels of testosterone, thus affecting spermatogenesis (Jensen et al., 2004).

Levels of subcutaneous and visceral fat have both been associated with reduced levels of free testosterone in men (Schneider et al., 1979; Tchernof et al., 1995; Jensen et al., 2004; Winters et al., 2006; Pasquali et al., 2007; Chavarro et al., 2010; MacDonald et al., 2010). Furthermore, adipocytokines (such as the pro-inflammatory cytokines TNF and IL-6) inhibit the production of testosterone by negatively feeding back to the hypothalamus. Low levels of testosterone have also been shown by CT scanning to correlate with overall obesity, increased waist circumference and the increased accumulation of visceral fat (Svartberg et al., 2004).

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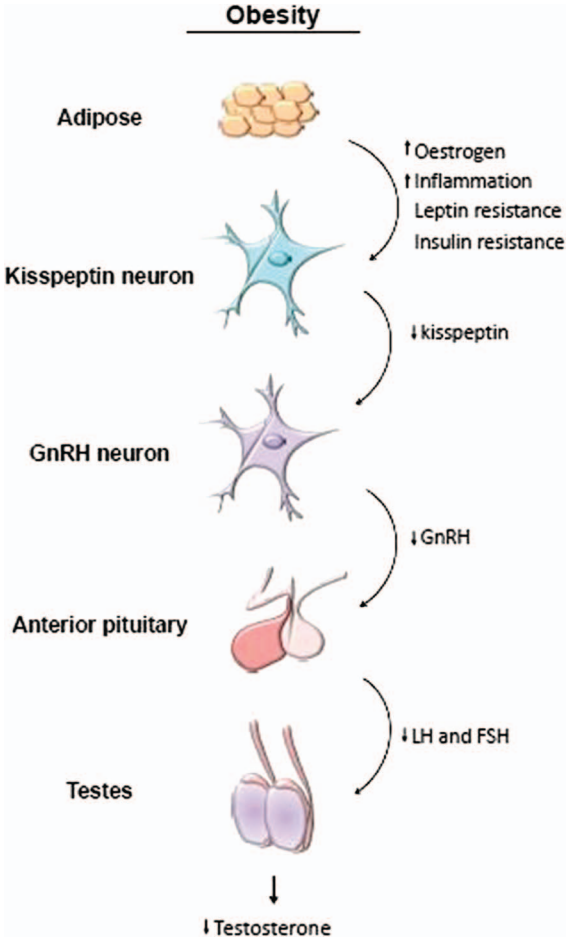

Figure 1. Effects of obesity upon kisspeptin neuron are hypothesised as the central pathway linking obesity to testosterone deficiency and subsequent male sub-fertility. Excess adipose tissue results in increased circulating oestrogen, a chronic state of inflammation, and resistance to leptin and insulin. These effects upon the kisspeptin neuron result in reduced levels of kisspeptin production, consequently lowering GnRH, LH and FSH release and ultimately reducing testosterone production and affecting spermatogenesis.

Obesity-related endocrine disruption

Obesity causes other endocrine changes in the human body, such as changes in the production and regulation of insulin, sex-hormone-binding-globulin (SHBG), leptin, and inhibin B. Changes in the circulating levels of these hormones impact the testosterone:oestrogen ratio, ultimately impairing spermatogenesis (Figure 2).

Testosterone plays a key role in insulin regulation, metabolism of lipids and body composition (Jones, 2010). Hyperinsulinaemia has been shown to have an inhibitory effect on spermatogenesis with a significantly higher level of nuclear and mitochondrial DNA damage found in sperm from affected individuals (Agbaje et al., 2007). Increasing BMI and waist circumference is also associated with reduced SHBG levels in the serum (Jensen et al., 2004; Fejes et al., 2005; Winters et al., 2006; Pasquali et al., 2007; Chavarro et al., 2010; Hajshafiha et al., 2013). SHBG is a glycoprotein which binds sex hormones such as testosterone and oestradiol in order to inhibit their biological activity. Hyperinsulinaemia from obesity-related insulin resistance causes the hepatic production of SHBG to decline, resulting in more biologically active oestrogen to negatively feedback onto the HPG axis. This fall in SHBG levels may be a homeostatic mechanism to maintain an adequate level of free testosterone, due to the lowered serum levels of testosterone seen in obese males (Chavarro et al., 2010).

There is a strong correlation between serum leptin, a hormone secreted by adipocytes, and body fat percentage. Leptin not only stimulates the satiety centre via hypothalamic-mediated effects, but also functions as a metabolic and neuroendocrine hormone in regulating sexual maturation and reproduction, indicating that white adipose can act as an endocrine organ (Jope et al., 2003; Wang et al., 2008; Hofny et al., 2010; DuPlessis et al., 2010). Mounting evidence reports a higher prevalence of obesity and high circulating levels of leptin in infertile men (Wang et al., 2008; DuPlessis et al., 2010; Farooq et al., 2014). Fat gain due to leptin deficiency caused by the *ob*/*ob* gene mutation is well studied; however, a majority of obese patients present with elevated serum leptin levels (Considine et al., 1996). Leptin normally stimulates GnRH release; however, the excess leptin associated with obesity causes the HPG axis to become resistant to leptin (Isidori et al., 1999; Rao et al., 2013). Due to the presence of leptin receptors in testicular tissue, and on the plasma membrane of sperm themselves, it is likely that elevated leptin levels in the serum affect spermatogenesis in obese males. Leptin inhibits stimulation on Leydig cells by the gonadotropins, resulting in a further decline in testosterone production. It has been reported that excess leptin from adipose tissue has deleterious effects upon sperm production and results in increased germ cell apoptosis in testes (Isidori et al., 1999). It is hypothesised that due to the presence of leptin receptors on sperm, leptin might directly affect spermatogenesis via endocrine mechanisms independent of the HPG axis; however, the true extent of this theory is yet to be investigated and proven (Jope et al., 2003; Ishikawa et al., 2007).

The production of inhibin B by Sertoli cells is the most effective marker for normal spermatogenesis. Inhibin B is a growth-like factor which acts in the testes to inhibit FSH production and to stimulate testosterone production by Leydig cells (Palmer et al., 2012a). The reduced levels of inhibin B found in obese males is indicative of seminiferous tubule dysfunction and is hypothesised to be due to a lower number of Sertoli cells (Jensen et al., 2004; Winters et al., 2006; Aggerholm et al., 2008; Pauli et al., 2008; MacDonald et al., 2010); however, a compensatory increase in FSH levels in response to low inhibin B has not been observed, indicating a potential for partial dysregulation of the HPG axis (Palmer et al., 2012b). These endocrine disruptions caused by obesity ultimately cause further reduction in the levels of testosterone and impair spermatogenesis, thus compromising fertility.

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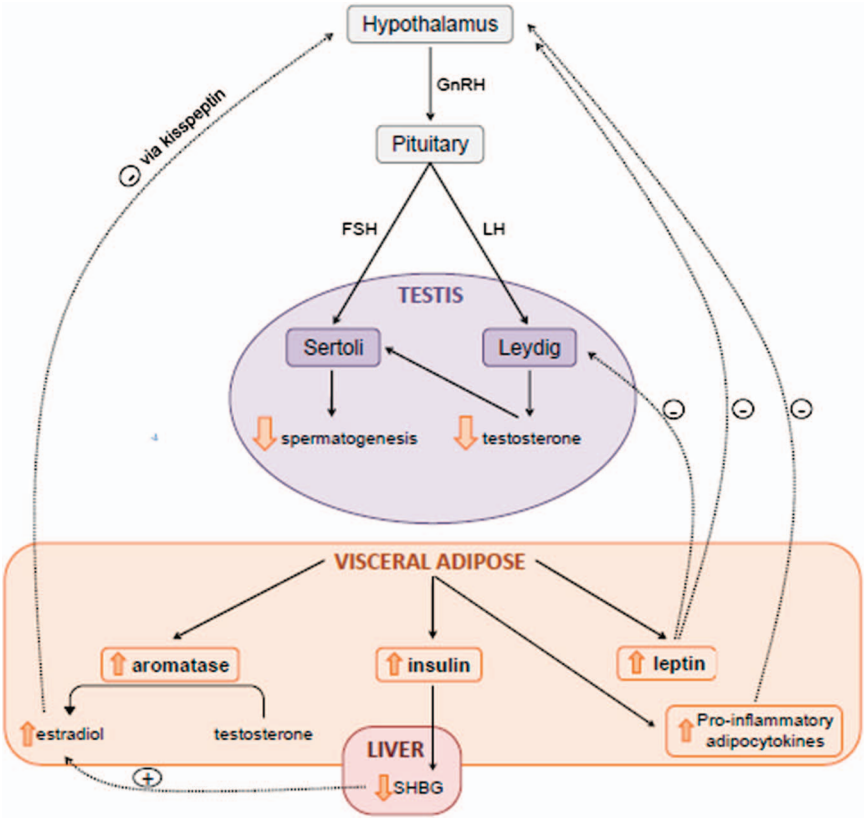

Figure 2. The effects of excess visceral adipose tissue on the HPG axis. Increased amounts of adipose tissue increase the quantity and activity of aromatase which converts testosterone to oestradiol in adipocytes. Oestradiol inhibits the HPG axis via kisspeptin neurons, leading to decreased production of testosterone. Excess adipose causes insulin resistance, resulting in increased levels of insulin which decrease sex-hormone-binding-globulin production in the liver, leading to increased levels of free oestrogen. Adipose tissue produces pro-inflammatory adipocytokines and leptin which effect the HPG through negative feedback. Leptin further inhibits the stimulation of gonadotropins on Leydig cells leading to decreased androgen production from the testes.

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Impaired spermatogenesis affects fertility

Effects upon traditional WHO semen parameters

Interestingly, studies investigating how increased BMI might affect routine semen parameters have yielded conflicting results. While it has been reported that obese men are three times more likely to exhibit a reduction in sperm quality compared with men of normal weight (Sharma et al., 2013; Shulka et al., 2014), the true effect of obesity upon semen quality is a source of much debate. Numerous studies have shown that there is no relationship between increased BMI and one or more of the following semen parameters: sperm concentration, count, morphology, motility and ejaculate volume (Jensen et al., 2004; Fejes et al., 2006; Aggerholm et al., 2008; Hammoud et al., 2008; Paul et al., 2008; Nicopoulou et al., 2009; Chavarro et al., 2010; MacDonald et al., 2010; Martini et al., 2010; Povey et al., 2012; Hajshafiha et al., 2013; Eisenberg et al., 2014; Pacey et al., 2014). Conversely, other studies show that BMI is associated with one or more of the following: sperm concentration, count, motility or ejaculate volume (Jensen et al., 2004; Fejes et al., 2006; Hammoud et al., 2006; Kort et al., 2006; Hofny et al., 2010; Chavarro et al., 2010; Sermondade et al., 2013; Eisenberg et al., 2014; Hadjkacem et al., 2015). The exact cause of poor semen parameters in obese men is difficult to assign due to a paucity of studies specifically investigating treatment of infertility in obese men, conflicting results in the studies that do exist as well as comorbidities such as cardiovascular disease, sleep apnoea and diabetes which can also affect fertility.

The lack of conclusive evidence with regard to the specific association of obesity and semen quality suggests that spermatogenesis may require only a minimum threshold level of hormonal regulation, and can continue despite temporal fluctuation (MacDonald et al., 2010). Furthermore, there exists insufficient evidence describing the effect of weight loss on rescuing sperm production and subsequent fertility. The conflicting results evident in existing literature could also represent the fact that BMI is a poor measure of body fatness (Nguyen et al., 2007). Further conflict could have arisen from the chosen sample populations not being representative of the general population as many studies were carried out in fertility clinics showing bias towards a population of sub-fertile men, from confounding lifestyle factors of impaired sperm function (including smoking, alcohol consumption, recreational drug use or co-pathologies), or under-reporting in self-reporting of lifestyle factors and BMI (Palmer et al., 2012a). However, recent studies examining lifestyle data from the large multicentre

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Chemical and Pregnancy Study (Chaps-UK) specifically aimed to control for the possibility of confounding bias in response to questions on common lifestyle factors. The study did this by only questioning patients who were unaware of their semen analysis results (Povey et al., 2012; Pacey et al., 2014).

Another important concern to take into account when analysing the effects of male obesity upon semen abnormalities is the potential confounding effect of maternal obesity and whether this leads to semen abnormalities in male offspring. It was hypothesised in 2007 that maternal obesity could have a programming effect upon testicular development in foetal life (Ramlau-Hansen et al., 2007). The authors observed that the sons of mothers who were overweight or obese during pregnancy were more likely to be overweight at birth and exhibit a high BMI in adulthood compared with the sons of normal-weight mothers. It was also suggested that higher free oestrogen levels in mothers (and hence the foetus) could interfere with normal testicular development and future fertility (Ramlau-Hansen et al., 2007). More recently, the same group reported that there was no obvious relationship between high birth weight/pre-pubertal body fat and semen quality in young adult life, suggesting that the effects of maternal obesity during pregnancy are unlikely to have an effect upon semen quality and subsequent fertility (Ramlau-Hansen et al., 2010).

The discrepancies in existing data relating obesity to traditional semen parameters, as well as the confounding variables evident in such studies, have led to the development of rodent models of paternal obesity to help better investigate the effects of obesity on male fertility. It is hoped that such models may, in future, provide a more specific hypothesis.

Deleterious effects upon molecular mechanisms in sperm

While traditional semen parameters are an important measure for male fertility, it is becoming more apparent that the content and molecular structure of sperm is critical in generating a healthy pregnancy. Male obesity is associated with reduced pregnancy rates and an increase in pregnancy loss in couples undergoing ART (Hinz et al., 2010; Keltz et al., 2010; Bakos et al., 2011a). Interestingly, one study noted that fertilisation rate was higher among obese men than men of normal weight for conventional *in vitro* fertilisation (IVF) cycles, and that there were no significant associations between male BMI and poor-quality embryos or cleavage rate (Colaci et al., 2012). However, this same study showed that the odds of live birth in couples with obese male partners undergoing intracytoplasmic sperm injection (ICSI) was 84% lower than men with normal BMI and concluded that there is a possible deleterious effect of male obesity on the odds of having a live birth rate (Colaci et al., 2012). It should be noted, however, that if male BMI influences whether patients are treated with ICSI, stratifying data by ICSI may lead to over adjustment bias and thus confound the observed outcomes (Schliep et al., 2015). Conversely, other studies report that for obese patients, rates of fertilisation (Keltz et al., 2010) and live birth rates (Petersen et al., 2013) are reduced following IVF but not following ICSI, suggesting impairment in sperm binding. In support of these clinical findings, mouse models of obesity, maintained upon a high-fat diet, have shown impaired sperm binding and capacitation compared with healthy controls (Bakos et al., 2011b; Palmer et al., 2012b). A recent study also reported that sustained high protein-tyrosine phosphatase 1B (PTP1B) activity in the sperm of obese mice may represent a vital link between obesity and sub-fertility (Lei et al., 2014). PTP1B is upregulated by pro-inflammatory factors, such as those released during the chronic inflammatory state of obesity. High levels of PTP1B impairs the reassembly of SNARE proteins causing deleterious effects in the sperm acrosome reaction, and a correlation was identified between high expression and activity of PTP1B and impaired acrosomal exocytosis in sperm. Furthermore, PTP1B is implicated in negative regulation of leptin and insulin signalling (Lei et al., 2014).

It should be kept in mind that in many of these studies, the confounding effect of maternal obesity is often not taken into account when associating outcomes to the incidence of male obesity. A recent study reported that weight status (overweight or obese) does not influence fecundity in couples undergoing infertility treatment. In fact, Schliep et al. (2015) investigated the effects of both male and female BMI on pregnancy and birth rates following IVF, and after adjusting for partner BMI, found no significant differences between fertilisation rate, embryo score, pregnancy or live birth rate compared with normal-weight controls.

Oxidative stress as a causative mechanism of sub-fertility

Obesity causes the body to be in a chronic inflammatory state and it is hypothesised that due to the higher metabolic rates required to maintain normal biological processes, there is an increase in the formation of reactive oxygen species (ROS) which can induce damage to DNA and plasma membrane integrity in sperm, as well as increase stress on the testicular environment (Esposito et al., 2004; Dandona et al., 2005; Agarwal et al., 2006; DuPlessis et al., 2010). Studies in humans have shown a positive correlation between levels of BMI and sperm oxidative stress in males (Tunc & Tremellen, 2009) and rodents (Bakos et al., 2011b), which has further been associated with reduced sperm motility, reduced acrosome reaction and lower embryo implantation rates following IVF (Zorn et al., 2003; Aitken & Baker, 2006; Aziz et al., 2004).

An excess of scrotal adipose tissue may alter spermatogenesis by increasing testicular temperature or by impacting upon intra-testicular signalling (Cabler et al., 2010). Physiological elevation in scrotal skin temperature has been associated with substantially reduced

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sperm motility and concentration, concomitant with increased levels of sperm DNA damage and oxidative stress (Paul et al., 2008; Shiraishi et al., 2010; DuPlessis et al., 2010). Increased apoptosis of spermatozoa is relatively common in obese males since phosphatidylserine externalisation is increased and mitochondrial membrane potential is lowered (La Vignera et al., 2012). The potential for impaired acrosome reaction ability and the conceivable negative effects of obesity-impaired spermatogenesis upon semen parameters via oxidative stress provides a likely explanation for the sub-fertile status of obese men.

Trans-generational inheritance of obesity

It is suggested that paternal obesity at the time of conception can affect the health of resultant offspring. Epidemiology studies have shown that obese fathers have a higher likelihood of fathering obese children (Li et al., 2009); however, the individual effects that genetic, epigenetic and environmental factors contribute to this phenomenon cannot be readily partitioned for discrete investigation. Therefore, animal models of paternal obesity are being increasingly relied on. There has been recent evidence from such models that paternal obesity compromises both the metabolic and reproductive health of first- and second-generation offsprings (Fullston et al., 2012), as well as influencing the susceptibility of offspring to obesity and diabetes (Mitchell et al., 2010; Ng et al., 2010). First-generation offsprings have identified compromised gametes with increased oxidative stress in sperm, changes in the mitochondrial function of oocytes as well as increased fat mass in females (Fullston et al., 2012). A hypothesis known as 'trans-generational epigenetic inheritance' now purports that molecular changes resulting from impaired spermatogenesis due to obesity, such as changes to DNA methylation, histone acetylation or non-coding RNA levels in sperm, are transmitted to the embryo and consequently affect subsequent development (Youngson & Whitelaw, 2011; Daxinger & Whitelaw, 2012; Palmer et al., 2012a). This represents an interesting area which needs to be investigated further and could help to develop and improve infertility treatments.

Epigenetic inheritance

DNA methylation is a normal requirement for spermatogenesis. For example, sperm methylation is required for inactivation of the X chromosome during meiosis and for the establishment of paternally imprinted genes in sperm (Ooi & Henikoff, 2007). Analysis of human spermatogenesis indicates the presence of DNA methyltransferase proteins during the spermatogenic cycle, which coincide with the establishment of methylation imprinting in sperm (Jenkins & Carrell, 2012). Throughout spermatogenesis these imprints are maintained, suggesting that they are a key molecular event (Marques et al., 2011). While little is known on the direct impact of obesity on the methylation status of DNA in germ cells, various metabolic disorders, which are commonly associated with obesity, including type-2 diabetes, modify DNA methylation status in somatic tissues, and are thought to have an additional effect on sperm DNA methylation (Barres & Zierath, 2011). The hypomethylation of repeat elements and imprinted genes have been associated with increased levels of sperm DNA damage and reduced pregnancy rates (El Hajj et al., 2011; Minor et al., 2011; Nanassy & Carrell, 2011; Tunc et al., 2011).

Histone acetylation is vital for the replacement of histones by protamines, which play a critical role in protecting sperm DNA (Francis et al., 2014), and mouse models maintained upon a high-fat diet exhibit alterations in the acetylation of late round spermatids, resulting in increased levels of DNA damage (Gaucher et al., 2010; Palmer et al., 2011). Furthermore, it has been proposed that acetylated histones may have an important effect on embryogenesis via the regulation of gene expression. However, the extent of histone replacement varies widely on a species-specific basis. In human sperm, 15% of histones remain following protamination, compared with only 1% in murine models. The retention of a proportion of histones in human sperm is believed to allow pluripotent regulatory genes (such as *Nanog, Oct 4* and *Sprout*) to remain histone-bound with loci capable of somatic cell histone modifications, allowing for their immediate activation and expression post-fertilisation, thus forming the basis for paternal programming in offspring (Farthing et al., 2008). Epigenetic modifications to acetylation of these loci, or to DNA methylation, may therefore differ in the sperm of obese versus non-obese males, thus affecting subsequent development of the offspring. However, investigative studies of this potential mechanism remain ongoing. Furthermore, studies looking into the trans-generational effects of underweight males should also be undertaken to further investigate the trans-generational effects of weight on DNA integrity and sperm RNA levels.

Sperm RNA and obesity

Mature sperm contain a regulated reserve of mRNA and non-coding RNA thought to be important for successful fertilisation and subsequent embryonic development (Ostermeier et al., 2004; Lalancette et al., 2009; Paradowska-Dogan et al., 2014). Sperm RNA was originally dismissed as residual from spermatogenesis; however, the presence of non-coding RNA in sperm of many species targeting a multitude of gene sequences unrelated to spermatogenesis suggests that the sperm RNA is more than just a residual relic and may have post-fertilisation functions including transmission of acquired characteristics (Miller & Ostermeier, 2006; Sendler et al., 2013; Gapp et al., 2014). It has been demonstrated that offspring show phenotypes of variable severity following inhibition of miRNA in male pronulei of fertilised zygotes depending on the miRNA

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ratio, indicating these RNAs play a role in oocyte development during fertilisation and early embryo development (Miller & Ostermeier, 2006). It remains unknown, however, whether the RNA by some means marks the genome before entry into the ooplasm, at fertilisation, of some point after fertilisation.

Studies have shown significant differences in the levels of mRNA transcripts within the testes of obese and lean mice (Ghanayem et al., 2010). However, the potential role of sperm RNA, particularly in terms of functionality and a potential feature of fertilisation and embryo development, remains a topic of some debate and represents a particular focus of many research groups.

Sperm DNA integrity in sub-fertile obese men

Numerous studies, carried out in both human and animal models, have identified a relationship between obesity and a reduction in the DNA integrity of sperm, which would thus have consequential implications upon fertilisation and embryonic development (Kort et al., 2006; Kriegel et al., 2009; Chavarro et al., 2010; Bakos et al., 2011b; Fariello et al., 2012; La Vignera et al., 2012). In two different mouse models of obesity (high-fat diet and leptin deficiency) increased BMI was successfully correlated with increased levels of sperm DNA fragmentation (Duale et al., 2014). An increased percentage of sperm with abnormally compacted chromatin, and an increased sperm DNA fragmentation index, was also detected in males with a BMI greater than 25 kg/m^2 (Kort et al., 2006; La Vignera et al., 2012). Conversely, a recent study by Eisenberg showed that increased BMI had no effect on the sperm DNA fragmentation index (Eisenberg et al., 2014), further suggesting that BMI may not be an appropriate index to use in such studies.

Solutions to obesity-related sub-fertility

Developing treatments for infertility is challenging, as the nature of fertility is multifactorial. In addition to genetic or pathological infertility, there are many lifestyle factors which can affect reproductive health such as nutrition, weight, exercise, stress, environmental exposures and drug use (Sharma et al., 2013). Moreover, there are numerous lifestyle choices which could lead to obesity and its associated diseases and sub-fertility. One major challenge in investigating how to treat sub-fertility associated with lifestyle factors is in considering how lifestyle changes leading to sub-fertility are likely to influence both male and female counterparts in a given couple. Therefore, if a male is obese and presenting with sub-fertility, the lifestyle choices leading to his obesity are highly likely to affect his female partner also; therefore, it is more than likely that her weight could also be a contributory factor in the couple's infertile status.

An individual's weight is often related to their eating habits and levels of activity. If one member of a couple is obese, there is a high likelihood that their partner may have a similar lifestyle and is also overweight or obese. Lifestyle changes though diet modifications and exercise can lead to gradual weight loss and thus help to overcome obesity and its associated preventable diseases. Several studies in obese males have reported that weight loss through lifestyle changes resulted in increased SHBG and serum testosterone levels, as well as reduced levels of insulin and leptin (Kaukua et al., 2003; Niskanen et al., 2004).

Since obesity appears to exert influence upon markers for male infertility, efforts have been undertaken to investigate whether measures taken to reverse the unhealthy consequences of obesity can also reverse the deleterious effects upon fertility. When couples seek infertility treatment and male factor infertility is diagnosed, most men present with a reduced ratio of testosterone to oestrogen (Luboshitzky et al., 2002). Pharmacological interventions via medication can be used to treat obesity by addressing weight loss via appetite suppressants, or to treat the effects of obesity upon the male reproductive tract. Aromatase inhibitors can be prescribed for males presenting with infertility problems, and who exhibit elevated oestrogen and reduced testosterone levels, in order to prevent the excessive conversion of testosterone to oestrogen (Elkhiat & Fahmy, 2011; Schlegel, 2012). Studies have shown that the administration of aromatase inhibitors is not only effective at restoring normal hormone levels, but can also normalise spermatogenesis and semen parameters (Raman & Schlegel, 2002; Zumoff et al., 2003; Roth et al., 2008). While these changes show some improvements in markers for fertility, further investigation into the direct effects of such treatment and the potential restoration of fertility are needed.

Conclusions

Increased urbanisation and industrialisation in the Western world has promoted a sedentary lifestyle and unfavourable diet in the general population leading to an increased incidence of obesity (Meldrum et al., 2012; Stefan et al., 2013). Studies have observed a parallel decrease in male fertility potential over the past decades in regions where obesity is prevalent (Swan et al., 2000). The diagnosis and treatment of reduced fertility in obese men requires an insight into the underlying pathology, which has hormonal, mechanical, molecular and psychosocial aspects. The aetiology is multifactorial, with emerging evidence showing that obese men having a greater risk of suffering from a dysregulated HPG axis and thus endocrine profile, impaired spermatogenesis and abnormal semen parameters. Emerging evidence shows that obesity negatively affects male reproductive potential, by lowering the testosterone:oestrogen ratio, reducing sperm quality, altering the structure of germ cells in the testes and altering sperm RNA.

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While several studies demonstrate short-term improvement in markers for male fertility following weight loss via lifestyle modifications or surgical intervention, unfortunately data pertaining to the long-term success of such interventions are lacking. Due to the complex interplay of factors contributing to subfertility associated with obesity, there is a need for a multifaceted approach for further understanding and development of treatments.

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