Testosterone: a metabolic hormone in health and disease

Daniel M Kelly and T Hugh Jones

1Department of Human Metabolism, Medical School, The University of Sheffield, Sheffield S10 2RX, UK 2Robert Hague Centre for Diabetes and Endocrinology, Barnsley Hospital NHS Foundation Trust, Gawber Road, Barnsley S75 2EP, UK

Abstract

Testosterone is a hormone that plays a key role in carbohydrate, fat and protein metabolism. It has been known for some time that testosterone has a major influence on body fat composition and muscle mass in the male. Testosterone deficiency is associated with an increased fat mass (in particular central adiposity), reduced insulin sensitivity, impaired glucose tolerance, elevated triglycerides and cholesterol and low HDL-cholesterol. All these factors are found in the metabolic syndrome (MetS) and type 2 diabetes, contributing to cardiovascular risk. Clinical trials demonstrate that testosterone replacement therapy improves the insulin resistance found in these conditions as well as glycaemic control and also reduces body fat mass, in particular truncal adiposity, cholesterol and triglycerides. The mechanisms by which testosterone acts on pathways to control metabolism are not fully clear. There is, however, an increasing body of evidence from animal, cell and clinical studies that testosterone at the molecular level controls the expression of important regulatory proteins involved in glycolysis, glycogen synthesis and lipid and cholesterol metabolism. The effects of testosterone differ in the major tissues involved in insulin action, which include liver, muscle and fat, suggesting a complex regulatory influence on metabolism. The cumulative effects of testosterone on these biochemical pathways would account for the overall benefit on insulin sensitivity observed in clinical trials. This review discusses the current knowledge of the metabolic actions of testosterone and how testosterone deficiency contributes to the clinical disease states of obesity, MetS and type 2 diabetes and the role of testosterone replacement.

Introduction

There has been an alarming increase, of epidemic proportions, in both obesity and diabetes in the general population with increased cardiovascular risk associated with type 2 diabetes mellitus (T2DM) and/or metabolic syndrome (MetS). MetS is defined as the presence of at least three of the following components: central obesity, hyperglycaemia (including T2DM), hypertension, hypertriglyceridaemia and low HDL-cholesterol (HDL-C). The MetS, a condition recognised by the World Health Organization, is associated with an increased risk of myocardial infarction, stroke and cardiovascular death. Reduced insulin sensitivity (known as insulin resistance) is the central biochemical defect associated with MetS and T2DM. Central obesity, hepatic steatosis and intracellular fat in muscle cells as well as lack of exercise and genetic factors precipitate the development of insulin resistance. Insulin resistance in turn promotes the development of glucose intolerance, hypertriglyceridaemia, low HDL-C, hypertension,
endothelial dysfunction and a proinflammatory milieu, which combine to promote atherogenesis.

Men develop coronary artery disease and experience premature coronary events earlier than women, increasing the risk of cardiovascular mortality by more than twofold. This led to the belief that testosterone per se exerts a detrimental influence upon the cardiovascular system; however, evidence has emerged over recent years to suggest that a number of the cellular mechanisms intimate to the atherosclerotic process are beneficially modulated by testosterone. Indeed, it is well established that total and biologically available testosterone in men decreases with age and the age-associated decline may be related to the increased prevalence of cardiovascular disease (CVD) and comorbidities. In fact, testosterone deficiency has been reported in population studies to be associated with an increase in all-cause mortality, and this has been shown to be accounted for mainly by CVD (Khaw et al. 2007, Vikan et al. 2009, Araujo et al. 2011). Moreover, accumulating evidence suggests that testosterone deficiency is an independent cardiovascular risk factor and many recent reviews have focussed on the link between hypogonadism, MetS, T2DM and CVD (Makhsida et al. 2005, Shabigh et al. 2008, Yassin et al. 2008, Corona et al. 2009, Diaz-Arjonilla et al. 2009, Jones & Saad 2009, Stanworth & Jones 2009, Traish et al. 2009, Zitzmann 2009a, Grossmann et al. 2010, Jones 2010a,b, Muraleedharan & Jones 2010, Moulana et al. 2011, Wang et al. 2011, Saad et al. 2012, Salam et al. 2012).

Testosterone levels themselves are considered to be lowered by chronic disease, making the designation of a causal relationship difficult to delineate (Morris & Channer 2012). Androgen deprivation therapy (ADT) as treatment for prostate cancer is a unique situation where the direct effects of lowering testosterone can be observed. While ADT reduces tumour growth and survival, it also increases the risk of coronary heart disease, diabetes and cardiovascular death (Levine et al. 2010, Jones 2011). This supports a key role of testosterone in atheroprotection, noted by a science advisory from the American Heart Association (Levine et al. 2010). Testosterone replacement therapy (TRT) in androgen-deficient men is now slowly being recognised for its therapeutic potential in the management of MetS and T2DM as well as its known benefit on quality of life and sexual health. Remarkably, physiologically replacing testosterone in men with T2DM and low testosterone levels has been demonstrated to significantly improve survival (Muraleedharan et al. 2011, Shores et al. 2012). However, with some confounding results, a lack of long-term placebo-controlled trials and an uncertainty regarding the underlying mechanisms of action, TRT remains controversial and its use as a protective metabolic hormone in CVD is at the centre of great debate. This review focuses on some of the clinical, experimental and mechanistic evidence implicating a role for testosterone in cardio-metabolic disorders.

Testosterone deficiency and metabolic risk

Testosterone deficiency has a high prevalence in men with T2DM (Dhindsa et al. 2004, Corona et al. 2006, Ding et al. 2006, Kapoor et al. 2007a, Corona et al. 2009). Furthermore, low testosterone is associated with impaired insulin sensitivity, increased percentage of body fat, truncal obesity, dyslipidaemia, hypertension and CVD (see Wang et al. (2011)). Epidemiological studies have consistently reported that up to 40% of men with T2DM have testosterone deficiency (Dhindsa et al. 2004, Corona et al. 2006, 2009, Ding et al. 2006, Kapoor et al. 2007a). Two recent systematic reviews and meta-analyses support that endogenous total and free testosterone was lower in subjects with MetS compared with those without (Brand et al. 2010, Corona et al. 2011). Several longitudinal studies demonstrate a similar association with a low testosterone concentration independently predicting the future development of insulin resistance, MetS and T2DM (Haffner et al. 1996, Stellato et al. 2000, Oh et al. 2002, Laaksonen et al. 2004, Kupelian et al. 2006, Rodriguez et al. 2007, Selvin et al. 2007, Haring et al. 2009).

The causality of this relationship between low testosterone and metabolic disease is unclear with obesity-induced androgen deficiency and hypogonadism-induced obesity both likely contributing to a bidirectional effect on disease pathology. Indeed, increased body fat is a well-known clinical feature of hypogonadism, and men with MetS at baseline are at an increased risk of developing hypogonadism based on an 11-year follow-up (Laaksonen et al. 2005). The finding that obesity impairs testosterone levels while low testosterone levels promote increased fat deposition was initially proposed as the hypogonadal–obesity cycle hypothesis by Cohen (1999). Testosterone is converted to 17β oestradiol (E2) by the enzymatic activity of aromatase in adipose tissue. Thus, with higher adipocyte expression of aromatase comes a subsequent reduction of circulating testosterone. Falling testosterone promotes increasing adipocyte number and fat deposition, which gradually leads to a further lowering effect on testosterone levels. In addition, the majority of the normal negative feedback of testosterone on the hypothalamo–pituitary axis occurs
via its aromatisation (either in peripheral adipose tissue or centrally) to E₂ (Hayes et al. 2000, 2001). Therefore, the excess aromatase activity from increased adipocyte numbers in obese men results in the suppression of gonadotrophin-mediated testosterone secretion leading to progressive hypogonadism.

The hypogonadal–obesity–adipocytokine hypothesis (Fig. 1) extends Cohen’s theory and explains why the body cannot respond to low testosterone levels by the normal homoeostatic compensatory production of androgens via increased gonadotrophin secretion to stimulate the testis (Jones 2007). E₂ and the inflammatory adipocytokines tumour necrosis factor α (TNFα) and interleukin 6 (IL6) inhibit hypothalamic production of GNRH and subsequent release of LH and FSH from the pituitary. This, in turn, reduces gonadal stimulation and inhibits testosterone release, thus causing a state of hypogonadotrophic hypogonadism. Leptin, an adipose-derived hormone with a well-known role in regulation of body weight and food intake, also induces LH release under normal conditions via stimulation of hypothalamic GNRH neurons. GNRH neurons, however, exhibit little or no mRNA for leptin receptors (Finn et al. 1998). Kisspeptins are peptides secreted by specific neurons in the hypothalamus and may provide the functional link between leptin and downstream gonadal regulation as they play a central role in the modulation of GNRH secretion and subsequent LH release. Indeed, GNRH neurons in the hypothalamus possess the kisspeptin receptor and kisspeptin neurons express the leptin receptor (Roseweir & Millar 2009). In human obesity, whereby adipocytes are producing elevated amounts of leptin, the hypothalamic–pituitary axis becomes leptin resistant (Isidori et al. 1999, Mantzoros 1999). In addition, oestrogen receptors (ERs) androgen levels (4). Kisspeptin neurons are inhibited by oestradiol, inflammation and leptin resistance and thus reduce GNRH stimulation of the pituitary and subsequent LH release. Reduced LH pulse decreases gonadal stimulation and testosterone release, thus causing a state of hypogonadotrophic hypogonadism. Furthermore, leptin also directly inhibits the stimulatory action of gonadotrophins on the Leydig cells of the testis to decrease testosterone production. +, positive effect; −, negative effect (Jones 2010a,b).

Figure 1
The hypogonadal–obesity–adipocytokine hypothesis. High aromatase activity in adipocytes converts testosterone to oestradiol (1). Reduced tissue testosterone facilitates triglyceride storage in adipocytes by allowing increased lipoprotein lipase activity (2) and stimulating pluripotent stem cells to mature into adipocytes (blue arrow). Increased adipocyte mass is associated with greater insulin resistance (3). Oestradiol and adipocytokines TNFα, IL6 and leptin (as a result of leptin resistance in human obesity) inhibit the hypothalamic–pituitary–testicular axis response to decreasing
are demonstrated on kisspeptin neurons and there is evidence from animal studies that leptin resistance, inflammation and oestrogens inhibit neuronal release of kisspeptin (see George et al. (2010)). Beyond hypothalamic action, leptin also directly inhibits the stimulatory action of gonadotrophins on the Leydig cells of the testis to decrease testosterone production; therefore, elevated leptin levels in obesity may further diminish androgen status (Isidori et al. 1999). Moreover, increasing insulin resistance assessed by glucose tolerance test and hypoglycemic clamp was shown to be associated with a decrease in Leydig cell testosterone secretion in men (Pitteloud et al. 2005a).

ADT for the treatment of prostatic carcinoma in some large epidemiological studies has been shown to be associated with an increased risk of developing MetS and T2DM (Keating et al. 2006, Levine et al. 2010). Non-diabetic men undergoing androgen ablation show increased occurrence of new-onset diabetes and demonstrate elevated insulin levels and worsening glycaemic control (Keating et al. 2006, Derweesh et al. 2007). Prostate cancer patients with pre-existing T2DM show a further deterioration of insulin resistance and worsening of diabetic control following ADT (Haider et al. 2007). Indeed, a review of cross-sectional studies of men undergoing long-term (>12 months) ADT over the last 20 years reveals a higher prevalence of diabetes and MetS compared with controls (Shahani et al. 2008). The authors conclude that abdominal obesity and hyperglycaemia in relation to low testosterone were responsible for this higher prevalence, predisposing ADT patients to higher cardiovascular risk.

**Testosterone therapy**

Testosterone administration was first shown to improve glucose disposal and lower plasma insulin levels over a 3-month period in obese men (Márín et al. 1992a). A follow-on study over 8 months by the same group confirmed that testosterone therapy in men with central obesity reduced insulin resistance as assessed using euglycaemic–hyperinsulinaemic clamp studies (Márín et al. 1992b). TRT was first shown to improve insulin resistance in hypogonadal men with T2DM in 2006. Kapoor et al. (2006, 2007a) reported the first randomised double-blind placebo-controlled crossover study of testosterone therapy in hypogonadal men with T2DM. Once fortnightly i.m. injections of 200 mg testosterone esters over 3 months resulted in significant improvement in insulin sensitivity and glycaemic control (HbA1c −0.37%) as well as a reduction in waist circumference, serum leptin and total cholesterol. The testosterone replacement in men with metabolic syndrome or type 2 diabetes (TIMES2) study, a large multi-centre European randomised double-blind placebo-controlled trial (n=220), demonstrated that testosterone replacement (2% testosterone gel) in hypogonadal men improved insulin resistance after 6 and 12 months of therapy by 15 and 16% compared with placebo (Jones et al. 2011). It is important to recognise that this benefit is similar to that of metformin, a first-line drug in the treatment of T2DM. Both the TIMES2 and the Moscow studies (randomised double-blind placebo-controlled trial; n=184; 30-week duration; intramuscular testosterone undecanoate) showed significant benefits on insulin resistance in men with the MetS (Kalinchenko et al. 2010, Jones et al. 2011).

Testosterone replacement has also been demonstrated to improve glycaemic control in some other studies in men with uncontrolled diabetes but these were not placebo controlled (Boyanov et al. 2003, Heufelder et al. 2009). One of these trials did compare the effects of a diet and exercise programme with the same programme in combination with testosterone replacement in hypogonadal newly diagnosed men with T2DM (Heufelder et al. 2009). This study found a greater benefit on glycaemic control with testosterone replacement than those with diet and exercise alone. The inclusion criterion for the TIMES2 study was the presence of hypogonadism in men with T2DM and/or the MetS, so the cohort included both men with good as well as poor diabetic control. A benefit on HbA1c of testosterone therapy compared with placebo was observed after 9 months but not earlier (Jones et al. 2011).

Chronic cardiac failure is associated with a state of insulin resistance and also of testosterone deficiency. The cause of the reduced insulin sensitivity is related to the chronic inflammation with elevated levels, in particular, of TNFα and not obesity as this disease is associated with cachexia. TRT improves the insulin resistance but has no effect on body weight (Malkin et al. 2007a, Caminiti et al. 2009). The response to testosterone replacement of insulin sensitivity is in part dependent on the androgen receptor (AR). In the TIMES2 study, those subjects with more sensitive AR, as demonstrated by shorter CAG repeats in exon 1 of the gene encoding the AR, had a greater improvement of Homeostasis Model of Assessment - Insulin Resistance (HOMA-IR) in response to testosterone (Stanworth RD, Akhtar S, Channer & Jones 2012, unpublished observations). There was no effect of transdermal TRT on hepatic insulin clearance in testosterone-deficient men (Basu et al. 2007).
Several studies have shown that TRT in obese men reduces BMI and visceral fat mass (Rebuffé-Scrive et al. 1991, Márin et al. 1992a,b, 1995, Saad et al. 2007, 2008, Agledahl et al. 2008). In the double-blinded placebo-controlled Moscow study, 184 men suffering from both MetS and hypogonadism showed significant decreases in weight, BMI and waist circumference following 30 weeks of testosterone replacement to the normal range (Kalinchenko et al. 2010). Other TRT studies have also reported improved body weight, BMI and waist circumference in men with MetS, T2DM and/or hypogonadism (Wang et al. 2000, Boyanov et al. 2003, Woodhouse et al. 2004, Kapoor et al. 2006, Allan et al. 2008, Swartberg et al. 2008, Jones et al. 2011).

**Testosterone effects on lipids**

Circulating lipid profiles are linked with obesity as central body fat is associated with altered lipoprotein ratios and composition, contributing to the risk of atherosclerosis (James et al. 1997). Such a disruption of this balance between so-called ‘good’ and ‘bad’ lipids is associated with increased cardiovascular risk. Indeed, elevated triglycerides and a reduced HDL-C level are central to the MetS and elevated total and LDL-cholesterol (LDL-C) levels are common in T2DM, although they are not individual components of the MetS. This highlights the need for careful management of hyperlipidaemia in the prevention of cardiovascular events (Jones 2010b).

Low levels of testosterone have been associated with an atherogenic lipoprotein profile, characterised by high LDL and triglyceride levels (Wu & von Eckardstein 2003), and a negative correlation between serum levels of testosterone and total and LDL-C has been observed in cross-sectional studies (Barrett-Connor & Khaw 1988, Barrett-Connor 1992, Haffner et al. 1993, Simon et al. 1997, Barud et al. 2002). Additionally, a positive correlation between serum testosterone and HDL has been reported in both healthy and diabetic men (Simon et al. 1997, Van Pottelbergh et al. 2003, Stanworth et al. 2011). Moreover, patients undergoing ADT demonstrate increased total cholesterol and LDL-C (Dockery et al. 2003, Nishiyama et al. 2005, Braga-Basaria et al. 2006, Yannucci et al. 2006), elevated triglycerides and reduced HDL-C (Haffner et al. 1993), or all these indicators of atherogenic lipid profiles (Haider et al. 2007) when compared with baseline or controls. In contrast to these studies, however, Khaw et al. (2007) reported that LDL levels were increased in patients in the upper quartile of endogenous testosterone levels compared with the lower quartile, yet a positive association between HDL and testosterone level was apparent. A few cross-sectional studies, however, have found no association between serum lipid measurements and endogenous testosterone (Kiel et al. 1989, Denti et al. 2000).

The majority of data from studies investigating TRT in hypogonadal and eugonadal men show some improvements in lipid and lipoprotein profiles. Indeed, meta-analysis of clinical trials in hypogonadal men report that significant reductions in total cholesterol and LDL-C are associated with intramuscular TRT (Whitsel et al. 2001, Isidori et al. 2005, Jones & Saad 2009). Of particular interest, it has been reported that testosterone replacement reduces cholesterol and LDL-C in elderly men already treated with statins, indicating that TRT may be therapeutically beneficial beyond statin treatment alone (Jones & Saad 2009). Heufelder et al. (2009) were one of the few authors to demonstrate a significant reduction in serum triglycerides and a significant increase in serum HDL-C levels following 12 months of TRT in hypogonadal men with T2DM. Similarly, over a 1-year period of testosterone replacement, HDL levels were reported to increase in men with MetS (Saad et al. 2007), and in hypogonadal men over a shorter time period (Zitzmann & Nieschlag 2007). The majority of studies on the effect of testosterone on HDL-C, however, have generated contradictory results with either a decreases (Thompson et al. 1989, Bagatell et al. 1994) or no change (Zgliczynski et al. 1996, Uyanik et al. 1997, Boyanov et al. 2003, Malkin et al. 2004a, Kapoor et al. 2006). The reasons for the differences between the studies are unclear; however, it has been proposed that testosterone stimulation of reverse cholesterol transport may lead to increased consumption of HDL-C (Wu & von Eckardstein 2003). A long-term TRT investigation may support this hypothesis by demonstrating that after an initial fall in their serum concentrations, HDL-C levels return to baseline levels after 12 months (Jones et al. 2011).

**Potential metabolic mechanisms of testosterone action**

The mechanisms linking testosterone with insulin resistance and T2DM are still not fully understood and there are few published papers that have investigated potential mechanisms by which testosterone increases insulin sensitivity and regulates glucose and lipid metabolism. The major insulin-responsive target tissues, such as skeletal muscle, liver and adipose tissue, inadequately respond to the physiologic effects of circulating insulin in
T2DM. Impaired insulin sensitivity in these three tissues is characterised by defects in insulin-stimulated glucose transport activity, in particular into skeletal muscle, impaired insulin-mediated inhibition of hepatic glucose production and stimulation of glycogen synthesis in liver, and a reduced ability of insulin to inhibit lipolysis in adipose tissue. In addition, as a consequence of dissociated fatty acid (FA) release from adipose tissue surplus to energy requirements in other organs, fat deposition in non-adipose tissue including skeletal muscle and liver occurs as a ‘spillover’ effect (Yu & Ginsberg 2005). In turn, this lipid accumulation contributes to impaired insulin responsiveness and abnormalities in glucose control (Fig. 2). Indeed, fat in liver and muscle correlates more strongly with insulin sensitivity than abdominal fat in rats (Lim et al. 2008). A growing body of studies has pointed to the
presence of heterogeneity regarding insulin resistance and insulin sensitivity among different tissues (Stumvoll et al. 2000); therefore, the mechanisms by which testosterone may impart beneficial actions on the development of T2DM and MetS are likely to be tissue dependent and involve multiple targets of lipid and carbohydrate metabolism (Table 1).

Muscle

Testosterone deficiency is associated with a decrease in lean body mass, and relative muscle mass is inversely associated with insulin resistance and pre-diabetes (Srikanthan & Karlamangla 2011). As up to 70% of the body’s insulin sensitivity is accounted for by muscle, low testosterone may lead to insulin resistance via anabolic and/or metabolic effects on muscle (Pitteloud et al. 2005b). Currently, however, little is known regarding the influence of testosterone on insulin action in skeletal muscle and the subsequent consequences on glucose metabolism and T2DM.

Glucose metabolism

It has been long known that castration is followed by decreased muscle glycogen levels in rat perineal and levator ani muscles and that the administration of testosterone induces a considerable increase in glycogen content (Leonard 1952, Apostolakis et al. 1963, Bergamini et al. 1968). An equal increase in skeletal muscle glycogen synthesis is apparent in castrated male rats supplemented with testosterone, diminishing the elevated blood glucose levels seen in untreated controls (Ramamani et al. 1999). A testosterone-induced increase in glycogen synthase activity was implicated for the alteration in the rate of glycogen synthesis from blood glucose. Concurrently, testosterone administration returned the enhanced glycogen phosphorylase activity in castrated rats to a normal level, thus reducing glycogen breakdown and the subsequent rise in free glucose. By contrast, the rate of glycosogenesis was shown to be depressed by testosterone in rat skeletal muscle with increased glycogen content postulated rather as a result of decreased glycosogenolysis (Bergamini 1975). In perineal muscle, however, glycosogenesis was increased in response to testosterone, suggesting differential mechanisms in different tissue locations.

Insulin-stimulated glucose uptake into muscle and adipose tissue is largely mediated by the Glut4 glucose transporter isoform. Under normal resting conditions, most of the Glut4 molecules reside in membrane vesicles inside the cell. To increase glucose transport, GLUT4 translocates to the cell membrane in response to insulin via signalling through the insulin receptor, subsequent binding of insulin receptor substrate 1 (IRS1) and activation of intracellular signalling pathways (Bryant et al. 2002). Thus, several studies have demonstrated that diminished GLUT4 (SLC2A4) expression correlates with decreased insulin responsiveness, and defects at the level of the insulin receptor, IRS1 and GLUT4 expression have been observed in patients with T2DM (Pessin & Saltiel 2000). In agreement with androgen action on glucose control, GLUT4 and IRS1 were up-regulated in cultured adipocytes and skeletal muscle cells following testosterone treatment at low dose and short-time incubations (Chen et al. 2006). Similarly, testosterone treatment increased IRS2 mRNA in cells isolated from male human skeletal muscle biopsies (Salehzadeh et al. 2011). Sato et al. (2008)
Table 1 Influence of testosterone on targets of lipid and glucose homoeostasis

<table>
<thead>
<tr>
<th>Testosterone action</th>
<th>Tissue</th>
<th>Target function</th>
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<tbody>
<tr>
<td>Glucose homoeostasis</td>
<td></td>
<td></td>
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<tr>
<td>↑ Glut4</td>
<td>Muscle&lt;sup&gt;a,b,c,d&lt;/sup&gt;, liver&lt;sup&gt;c&lt;/sup&gt; and adipose&lt;sup&gt;a,b,c&lt;/sup&gt;</td>
<td>Glucose transporter protein involved in cellular glucose uptake</td>
</tr>
<tr>
<td>↑ IR</td>
<td>Liver&lt;sup&gt;e,f&lt;/sup&gt; and larynx&lt;sup&gt;g&lt;/sup&gt;</td>
<td>Insulin signalling</td>
</tr>
<tr>
<td>↑ IRS1</td>
<td>Muscle&lt;sup&gt;a&lt;/sup&gt;, adipose&lt;sup&gt;a&lt;/sup&gt; and liver&lt;sup&gt;f&lt;/sup&gt;</td>
<td>Insulin signalling</td>
</tr>
<tr>
<td>↑ IRS2</td>
<td>Muscle&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Insulin signalling</td>
</tr>
<tr>
<td>↑ Akt</td>
<td>Muscle&lt;sup&gt;e&lt;/sup&gt;</td>
<td>Insulin receptor signalling pathway</td>
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<tr>
<td>↑ Protein kinase C</td>
<td>Muscle&lt;sup&gt;h&lt;/sup&gt;</td>
<td>Key regulatory enzyme in glycolysis</td>
</tr>
<tr>
<td>↑ Phosphofructokinase</td>
<td>Muscle&lt;sup&gt;h,d&lt;/sup&gt;</td>
<td>Key regulatory enzyme in glycolysis</td>
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<tr>
<td>↑ Hexokinase</td>
<td>Muscle&lt;sup&gt;i&lt;/sup&gt;</td>
<td>Oxidative phosphorylation in mitochondrial respiration</td>
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<tr>
<td>↑ UQRCB</td>
<td>Muscle&lt;sup&gt;k&lt;/sup&gt;</td>
<td>Glycogenesis</td>
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<tr>
<td>↑ Glycogen synthase</td>
<td>Muscle&lt;sup&gt;e&lt;/sup&gt;</td>
<td>Glycogen breakdown</td>
</tr>
<tr>
<td>↓ Glycogen phosphorylase</td>
<td>Muscle&lt;sup&gt;lm&lt;/sup&gt;</td>
<td>Rate-limiting enzyme in the pentose phosphate pathway</td>
</tr>
</tbody>
</table>

| Lipid homoeostasis |        |                 |
|↓ AC5               | Adipose<sup>n</sup> | De novo lipogenesis |
|↓ ACC               | Liver<sup>r,u</sup>, sebaceous gland<sup>q,r</sup> and adipose<sup>l</sup> | FA synthesis |
|↑ ACC               | Prostate cancer cells<sup>1</sup> | Conversion of cholesterol to cholesteryl esters |
|→ ACAT1             | Sebaceous gland<sup>1</sup> | Receptor-mediated endocytosis of LDL |
|→ ACC               | Sebaceous gland<sup>1</sup> | Cholesterol efflux |
|↑ LDLr              | Liver<sup>p,u</sup> and adipose<sup>q,v</sup> | FA synthesis |
|↑ FAS               | Sebaceous gland<sup>1</sup> | Cholesterol synthesis |
|↑ FAS               | Prostate cancer cells<sup>1</sup> | Cholesterol synthesis |
|↑ HMG-CoA            | Sebaceous gland<sup>q,r</sup> and prostate cancer cells<sup>1</sup> | Cholesterol synthesis |
|↓ GPAT              | Sebaceous gland<sup>q,r</sup> | Triglyceride breakdown |
|↓ HSL               | Adipose<sup>x</sup> | Noradrenaline-stimulated lipolysis |
|↓ β-Adrenergic receptor | Adipose<sup>1</sup> | Lipolysis |
|↓ ATGL              | Adipose<sup>v</sup> | Triglyceride uptake |
|↑ LPL               | Adipose<sup>v,w,AA</sup> | Cholesterol efflux |
|↑ ApoE              | Liver<sup>p</sup> | Role in insulin resistance and lipid metabolism |
|↓ RBP4              | Adipose<sup>v</sup> | Key enzyme in FA metabolism |
|↓ Scd1              | Liver<sup>r,u</sup> | Key enzyme in cholesterol conversion to bile acid |
|↑ SCD1              | Liver<sup>BB</sup> | Selective uptake of cholesterol esters from HDL |
|↓ C7AH              | Liver<sup>BB</sup> | Central role in lipoprotein assembly, ApoB and VLDL secretion |
|↓ SR-1B             | Liver<sup>BB</sup> |             |
|↓ MTTP              | Liver<sup>BB</sup> |             |

| Master regulators |        |                 |
|↑ LXR              | Liver<sup>p</sup> | Regulator of glucose and cholesterol metabolism, FA synthesis and inflammation |
|↓ PPAR<sup>γ</sup> | Liver<sup>o</sup> and stem cells<sup>CC</sup> | Whole-body energy homoeostasis adipogenesis and inflammation |
|↑ SREBP-1c         | Sebaceous gland<sup>1</sup> and prostate cancer cells<sup>DD,EE</sup> | Regulator of de novo lipogenesis, cholesterol homoeostasis and glucose homoeostasis |
|↑ SREBP-1a         | Sebaceous gland<sup>1</sup> |             |
|↑ SREBP-1c         | Liver<sup>d</sup> |             |

ABC1, ATP-binding cassette 1; ACAT1, acyl-CoA cholesterol acyl transferase-1; ACC, acetyl-CoA carboxylase; ACS, acetyl-CoA synthetase; ApoE, apolipoprotein E; ATGL, adipose triglyceride lipase; C7AH, cholesterol 7α-hydroxylase; FAS, fatty acid synthase, GLUT4, glucose transporter-4; GPAT, glycerol 3-phosphate acyl transferase; HMG-CoA, hydroxymethylglutaryl coenzyme A; HSL, hormone-sensitive lipase; IR, insulin receptor; IRS, insulin receptor substrate; LDLr, LDL receptor; LPL, lipoprotein lipase; LXR, liver X receptor; MTTP, microsomal triglyceride transfer protein; PPARγ, peroxisome proliferator-activated receptor γ; RBP4, retinol-binding protein-4; Scd1, stearoyl-CoA desaturase 1; SR-1B, scavenger receptor class B member 1; SREBP-1c, sterol regulatory element binding protein 1c; UQRCB, ubiquinol cytochrome c reductase-binding protein.

<sup>a</sup>Chen et al. (2006); <sup>b</sup>Sato et al. (2008); <sup>c</sup>Muthusamy et al. (2009); <sup>d</sup>McLaren et al. (2012); <sup>e</sup>Parthasarathy et al. (2009); <sup>f</sup>Muthusamy et al. (2011); <sup>g</sup>Sesti et al. (1992); <sup>h</sup>Salzmann et al. (2011); <sup>i</sup>Bergmanni et al. (1968); <sup>j</sup>Petitclou et al. (2005b); <sup>k</sup>Ramamani et al. (1999); <sup>l</sup>Max & Knudsen (2005); <sup>m</sup>Santosa & Jensen (2012); <sup>n</sup>Lin et al. (2008); <sup{o}</sup>Kelly et al. (2012); <sup>p</sup>Hall et al. (1983); <sup>q</sup>Rosignoli et al. (2003); <sup>r</sup>Macotela et al. (2009); <sup>s</sup>Martín et al. (1995); <sup>t</sup>Macotela et al. (1997); <sup>u</sup>Chow et al. (2011); <sup>v</sup>McInnes et al. (2012); <sup>w</sup>Dicker et al. (2004); <sup>x</sup>De Pergola (2000); <sup>y</sup>Rebuffé-Schaeffer et al. (1991); <sup>z</sup>Max & Knudsen (2005); <sup>A</sup>Santosa & Jensen (2012); <sup>B</sup>De Pergola (2000); <sup>C</sup>Singh et al. (2002); <sup>D</sup>Huang et al. (2012); <sup>E</sup>Heemers et al. (2001).
demonstrated that GLUT4 expression and translocation was elevated following the addition of testosterone to cultured skeletal muscle cells of neonatal rats. Additionally, testosterone increased phosphorylation of Akt and protein kinase C (PKC), as key steps in the insulin receptor signalling pathways for regulation of GLUT4 translocation (Sato et al. 2008). These effects were blocked by a dihydrotestosterone (DHT) inhibitor, suggesting that local conversion of testosterone to DHT and activation of AR may be important for glucose uptake. Patients with Kennedy disease (a neuromuscular disorder) possess a genetic polymorphism with excess CAG repeats in exon 1 of the AR, leading to a condition associated with a relatively insensitive AR. In support of AR-dependent mechanisms, men with Kennedy disease have an increased risk of developing diabetes, thus providing further evidence of a link between impaired androgen status and diabetes (Stanworth et al. 2008, 2011, Zitzmann 2009b). Glut4 expression in the AR-deficient testicular feminised (Tfm) mouse, however, was shown to be up-regulated following testosterone replacement, suggesting some AR-independent actions (McLaren et al. 2012).

In addition to insulin signalling and glucose uptake, testosterone has been shown experimentally to influence key enzymes involved in glycolysis. Sato et al. (2008) reported that testosterone increased activity of phosphofructokinase and hexokinase in cultured rat skeletal muscle cells. In an early study, Bergamini et al. (1968) demonstrated a maximal 40% increase in hexokinase activity in castrated male rats 12 h after testosterone administration, with levels constantly above those of castrated rats over time. Preliminary work in the Tfm mouse, whereby affected animals present low endogenous testosterone levels and a non-functional AR, has also demonstrated that hexokinase-2 expression was significantly reduced in skeletal muscle tissue of Tfm mice compared with wild-type (McLaren et al. 2012). Testosterone treatment did not significantly alter hexokinase-2 expression, suggesting an AR-dependent action.

In addition, glucose oxidation as an early step in glycolysis was increased in isolated sebaceous glands from testosterone-treated castrated male mice compared with castrated controls (Sansone et al. 1971). This increased oxidation, however, was considered to parallel increased glucose use in the pentose phosphate pathway for the generation of NADPH+ and its subsequent utilisation in FA synthesis. Indeed, triglyceride, FA and wax ester were increased in the glands in a time-responsive manner rising from 24 h and reaching highest levels at 6 days post-testosterone injection. It is not clear whether castrate control tissue was investigated at all time points to eliminate the possibility of sebaceous gland lipid accumulation over time rather than a treatment effect. Glucose-6-phosphate dehydrogenase activity, the rate-limiting enzyme in the pentose phosphate pathway, was shown to be increased in rat levator ani muscle following administration of testosterone propionate, suggesting a potential action on NADPH+ formation and possibly lipogenesis (Max & Knudsen 1980, Max 1984).

Another potential mechanism for the beneficial effect of testosterone in diabetic men may be to increase the metabolic rate in skeletal muscle, promoting the acquisition of energy from adipose tissue and thus reducing fat mass. Pitteloud et al. (2005b) describes an inverse correlation between testosterone levels and adverse mitochondrial function, assessed by measuring maximal aerobic capacity (VO₂max) in men with varying degrees of glucose control. In addition, the expression of genes involved in mitochondrial oxidative phosphorylation from skeletal muscle biopsies was related to testosterone levels, impaired glucose tolerance and the presence of T2DM. Of these genes, ubiquinol cytochrome c reductase-binding protein (UQRCB) had the largest expression difference between normal and diabetic muscle and was correlated with testosterone and insulin resistance (Pitteloud et al. 2005b). UQRCB is involved in the activation of ubiquinol cytochrome c reductase, which plays a critical role in oxidative phosphorylation.

Interestingly, orchidectomy of male Wistar rats and associated testosterone deficiency induced increased absorption of glucose from the intestine in a recent study (Olorunshola et al. 2012). A paradoxical significant decrease in cellular glucose uptake in the gut was observed when compared with sham-operated controls, suggesting a concurrent decrease in glucose utilisation by the gut. Subcutaneous testosterone propionate administration at a dose of 2.5 mg/kg body weight in castrated rats returned both gut absorption and utilisation of glucose to sham levels. This offers another alternate mechanism by which testosterone may contribute to the regulation of blood glucose levels.

**Lipid metabolism** Muscle tissue additionally has a role in lipid metabolism. Fat is oxidised in the liver and extra-hepatic tissue such as skeletal muscle and this component of lipid metabolism may be influenced by testosterone. Adverse effects on energy expenditure and fat oxidation were observed in elderly males suffering from prostate cancer and undergoing androgen deprivation (Reis et al. 2009). Decreased fat oxidation and increased

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glucose oxidation was observed post-orchiectomy compared with pre-treatment. Likewise, testosterone deficiency induced by gonadal steroid suppression in healthy young men resulted in a significant decline in rates of lipid oxidation, with parallel changes in resting energy expenditure resulting in increased adiposity (Mauras et al. 1998). Furthermore, short-term (2 weeks) transdermal testosterone treatment stimulated whole-body fat oxidation and reduced the increased fat mass in testosterone-deficient men with hypopituitarism (Birzniece et al. 2009). Increased fat oxidation was not associated with an increase in resting energy expenditure or alterations in glucose oxidation leading the authors to postulate that a decrease in protein oxidation may be the source. Indeed, intramuscular TRT has been shown to reduce protein oxidation in hypogonadal men (Gibney et al. 2005). By contrast, orchidectomised mice treated with DHT resulted in obesity due to decreased fat oxidation and reduced energy expenditure while food consumption and locomotor activity remained unchanged (Movéreare-Skrtic et al. 2006). The decrease in total body fat oxidation was not associated with a decrease in rate-limiting enzymes involved in β-oxidation in skeletal muscle or liver. The authors suggest that DHT may be acting indirectly on fat oxidation by reducing glucose oxidation. The disparity in these studies may be due to the differential influence of different hormones in different metabolic environments. The response to energy requirements by switching between lipid, glucose and protein oxidation in skeletal muscle is essential for metabolic homoeostasis, with impairment of this termed ‘metabolic inflexibility’ (Kelley & Mandarino 2000).

Frederiksen et al. (2012a) recently demonstrated that testosterone may influence components of metabolic flexibility as 6 months of transdermal testosterone treatment in aging men with low–normal bioavailable testosterone levels increased lipid oxidation and decreased glucose oxidation during the fasting state.

Decreased lipid oxidation coupled with diet-induced chronic FA elevation is linked to increased accumulation of myocellular lipid, in particular diacylglycerol and/or ceramide in myocytes (Itani et al. 2002, Stratford et al. 2004). In turn, triglyceride and lipid build-up in muscle impairs insulin signalling leading to decreased insulin sensitivity, demonstrating the link between myocellular lipid and insulin resistance. By potentially enhancing lipid oxidation in muscle, improving circulating lipid profiles and sensitising myocyte insulin signalling and glucose metabolism, testosterone may protect against the detrimental myocellular consequence of dysregulated lipid metabolism in T2DM, obesity and MetS, although further investigation is required.

Liver

Glucose metabolism The liver has a prominent role in the maintenance of glucose and lipid homoeostasis through the function of multiple metabolic pathways. In addition to insulin, experimental data indicate that many other hormones influence hepatic glucose control. In the Chang human adult liver cell line, insulin receptor mRNA expression was significantly increased following exposure to testosterone. This resulted in increased insulin binding, as measured by radio receptor assay and elevated glucose oxidation compared with basal response (Parthasarathy et al. 2009). Sesti et al. (1992) also reported that testosterone and DHT treatment of human larynx carcinoma cell line (HEp-2) significantly increased insulin receptor mRNA levels and insulin receptor number as well as enhancing insulin responsiveness through elevated glucose utilisation. Similarly, testosterone administration in orchidectomised adult male rats increased insulin receptor mRNA and protein expression in liver tissue and was associated with a normalisation of the castration-induced impairment of glucose oxidation (Muthusamy et al. 2011). Serine phosphorylation of IRS1, known to attenuate insulin signalling by inhibiting tyrosine phosphorylation (Aguirre et al. 2002), was elevated in castrated mice, with testosterone treatment significantly improving this effect even beyond control levels (Muthusamy et al. 2011).

Testosterone deprivation via castration of male rats led to decreased expression of Glut4 in liver tissue, as well as adipose and muscle (Muthusamy et al. 2009). GLUT4 translocation, measured by the ratio of cytosolic to membrane protein fractions, was also inhibited. These cellular mechanisms were accompanied by an elevation of blood glucose, reduced insulin levels and decreased glucose uptake in adipose and skeletal muscle tissue. Physiologically, replacing testosterone in these animals restored Glut4 expression and glucose uptake to wild-type levels. Oestrogen treatment had a limited effect on these parameters. The direct actions of testosterone were unclear and the authors indicate that the impairment of Glut4 expression may result from castration-induced deficiency in insulin. By contrast, within the promoter region of the human insulin receptor gene, two functional oestrogen response elements have been identified, suggesting that testosterone actions may be

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via aromatisation (García-Arencibia et al. 2005). Indeed, oestrogen was found to increase the expression of insulin receptors in insulin-resistant HepG2 human liver cell line (Xie et al. 2003).

Lipid metabolism  Liver fat is correlated with all components of MetS, and obesity directly impacts on liver function. Visceral fat blood supply is cleared into the hepatic portal vein, in contrast to the peripheral fat, which is drained by the systemic circulation (Márin & Arver 1998). Consequently, the liver is exposed to products of adipocyte metabolism, such as free FA (FFA) and adipokines, in high concentrations and may induce metabolic disorders due to subsequent perturbation of liver metabolism. FFA decrease hepatic insulin binding and extraction, increase hepatic gluconeogenesis and increase hepatic insulin resistance. Ultimately, these effects lead to peripheral hyperinsulinaemia, systemic insulin resistance and hepatic steatosis. A reduction in adipocyte metabolism by testosterone would therefore reduce FFA production and, in turn, insulin resistance. The relationship between hepatic steatosis and serum testosterone concentrations has not yet received sufficient attention. Only one, albeit large-scale, population-based cross-sectional study reports an association between low serum testosterone concentrations and hepatic steatosis in men (Völzke et al. 2010). Two smaller studies report contrasting results in patients with hepatic steatosis as one reported low serum concentrations of testosterone and the other reported no significant differences in serum levels (Kley et al. 1975, Myking et al. 1987). Another study demonstrated through the generation of a hepatic AR knockout mouse model that a high-fat diet induced hepatic steatosis and insulin resistance in male but not in female mice (Lin et al. 2008). One of the contributing factors was hypothesised to be due to an increase in de novo lipid synthesis with loss of AR function, as hepatic expression of sterol regulatory element binding protein 1c (SREBP-1c), stearoyl-CoA desaturase 1 (SCD1), acetyl-CoA carboxylase (ACC (ACACA)) and proteasome proliferator-activated receptor γ (PPARγ (PPARG)), key enzymes in the regulation of FA synthesis, were up-regulated. Of interest, SCD1 is the rate-limiting enzyme of monounsaturated FA biosynthesis and increasing evidence implicates it as a novel control point in the pathogenesis of lipid-induced insulin resistance (Dobrzyn et al. 2010). Importantly, however, Lin et al. did not measure testosterone levels in high-fat diet-fed animals and thus could not determine whether increased hepatic steatosis was due to AR function or an obesity-related testosterone decline. By contrast, hepatic Scd1 mRNA expression was increased following DHT treatment in orchidectomised obese mice compared with placebo-treated controls (Movérare-Skrtic et al. 2006). Significantly elevated Scd1 expression also remained when compared to sham-operated controls, suggesting possible pharmacological effects of DHT administration.

Movérare-Skrtic et al. (2006) showed a modest increase in scavenger receptor class B member 1 (SR-1B) expression in the liver of castrated obese mice treated with DHT. Hepatic SR-1B is involved in selective uptake of cholesterol esters from circulating HDL facilitating reverse cholesterol transport. At the same time, microsomal triglyceride transfer protein was decreased by DHT, thus reducing apolipoprotein B-mediated very LDL (VLDL) secretion. Cholesterol 7α-hydroxylase, a key enzyme in bile acid formation and therefore removal of cholesterol from the body, was decreased following DHT administration in this study, leading to hepatic lipid accumulation due to increased cholesterol uptake but decreased removal (Movérare-Skrtic et al. 2006). Contrariwise, AR-independent effects on hepatic steatosis and lipid metabolism have been demonstrated in the Tfm mouse (Kelly et al. 2012). A high-cholesterol diet induced significant hepatic lipid accumulation in Tfm mice compared to wild-type, and intramuscular testosterone replacement significantly abrogated this effect. An AR-independent action on de novo lipogenesis was considered as testosterone administration reduced the elevated expression of FA synthase (FAS) and ACC observed in the Tfm mouse in addition to increasing apolipoprotein E (apoE), an important protein in cholesterol transport/efflux. A concomitant increase in hepatic liver X receptor (LXR), as a master regulator of glucose and cholesterol metabolism and inflammation, was also described, suggesting that some of the beneficial actions of testosterone on hepatic lipid accumulation and metabolism may occur via a LXR effect that is independent of the AR (Kelly et al. 2012). In aromatase null (ArKO) male mice, hepatic transcript expression of Fas and Scd1 was significantly elevated compared with wild-type males, but only Fas expression was lowered to wild-type level after ERα agonist treatment (Chow et al. 2011). This suggests that testosterone may confer some of its beneficial effects on hepatic lipid metabolism via conversion to E2 and subsequent activation of ERα.

Adipose tissue

Adipose tissue plays a major role in glucose homeostasis and insulin sensitivity through the regulation of lipid and
glucose metabolism. Rather than obesity per se being related to testosterone levels in men, adiposity and particularly the location of adipose distribution appear to influence both androgen concentrations and cardiovascular risk. Specifically, a strong inverse correlation between body fat and testosterone level is evident (Kapoor et al. 2005), with hypogonadal men exhibiting a reduced lean body mass and an increased fat mass, abdominal or central obesity (Seidell et al. 1990, Haafner et al. 1993, Phillips 1993, Couillard et al. 2000). Central adiposity may not fully correlate with the degree of visceral fat volume; therefore, more accurate methods for assessing visceral fat volume may provide more detailed investigation. Using computed tomography (CT) scanning, Tsai et al. (2000) showed an inverse correlation between the total testosterone levels of 110 men and accumulation of visceral fat, but not other fat depots, after a 7.5-year follow-up. Similarly, other studies using CT and MRI scanning confirmed this inverse relationship of testosterone with visceral fat (Seidell et al. 1990, Couillard et al. 2000, Garaulet et al. 2000). In a population of young men aged 20–29 years, Nielsen et al. (2012) showed by dual-energy X-ray absorptiometry and MRI that the level of visceral adipose tissue was inversely correlated with bioavailable testosterone. By contrast, there was no change in visceral fat mass in aged men with low testosterone levels following 6 months of transdermal TRT, yet subcutaneous fat mass was significantly reduced in another study of men with T2DM. Furthermore, prostate cancer patients undergoing ADT present increased central adiposity and percentage body fat and decreased lean mass (Smith et al. 2001, 2002, 2006) with the change in body fat demonstrated to be mainly subcutaneous and not in visceral fat depot, which is atypical for the MetS (Faris & Smith 2010). To the best of our knowledge, there are no mechanistic studies that address the differential response to testosterone in different adipose tissues.

Androgens have been shown to affect the expression of several key enzymes involved in lipogenesis. Using the hamster ear sebaceous gland model, DHT strongly induced the synthesis of triglycerides, squalene and cholesterol esters with increased expression of hydroxymethylglutaryl coenzyme A (HMG-CoA) reductase and synthase, ACC and glycerol 3 phosphate acyl transferase (GPAT) (Hall et al. 1983, Rosignoli et al. 2003). No effect was seen for the expression of FAS, acyl-CoA cholesterol acyl transferase-1 (ACAT1) and LDL receptor mRNA (Rosignoli et al. 2003). The mechanism of lipogenic gene up-regulation was considered to be via the SREBP pathway as DHT increased SREBF1 (both 1a and 1c isoforms) mRNA expression. SREBPs are considered master regulators of lipid homeostasis, controlling the expression of a range of enzymes required for endogenous cholesterol, FA, triacylglycerol and phospholipid synthesis (Brown & Goldstein 1999). Although DHT did not alter expression of SREBP cleavage-activating protein (SCAP), a chaperone protein responsible for SREBP activation, SCAP activity may still be a target for androgen action (Rosignoli et al. 2003). As this study only investigated the effects of DHT, any alternative AR-independent actions of testosterone may not have
been explicated. In addition, sebaceous glands are actively lipogenic, functioning to produce lipid containing sebum for the lubrication and waterproofing of the skin and hair. Indeed, expression of ATP-binding cassette 1 (ABC1), involved in cholesterol efflux, was also elevated by DHT, indicating that the increased lipids may be secreted from sebaceous glands (Rosignoli et al. 2003). Therefore, androgen stimulation of lipogenesis in this tissue may not be applicable to the major tissues involved in the pathogenesis of T2DM and MetS, although these studies do indicate the potential for androgen modulation of lipogenic gene expression.

In prostate cancer cell lines, a similar increase in SCAP expression and SREBP activity following androgen treatment has been described (Heemers et al. 2001). Indeed, androgen treatment of LNCaP cells resulted in a three- to fourfold stimulation of the steady-state mRNA levels of FAS and up to tenfold increase in FAS activity (Swinnen et al. 1997). HMG-CoA synthase and reductase as well as ACC expression was also elevated in the presence of synthetic androgen (Swinnen et al. 1997) reflective of a marked accumulation of cholesterol esters (Swinnen et al. 1996). Up-regulation of these lipogenic genes was again mediated via SREBP and SCAP, and supporting this notion, Heemers et al. (2004) identified an androgen response element located in intron 8 of the SCAP gene. These findings suggest that rather than influencing the expression of lipogenic enzymes individually, androgens may modulate the expression and/or activity of common transcription factors regulating their coordinate control (see Swinnen & Verhoeven (1998)). Prostate cells display greatly enhanced AR expression and growth, and progression of prostate cancer cells is driven by the activation of AR and lipogenesis with SREBP-1 central to this interaction (Huang et al. 2012). Therefore, again this tissue is specific in its functioning and may not allow extrapolation of study findings to other tissues.

In addition, testosterone appears to inhibit lipid uptake potentially via affecting the expression of adipocyte lipoprotein lipase (LPL). LPL resides on the extracellular surface of adipocytes and hydrolyses circulating triglyceride-rich lipoproteins to FA, which are taken up into the adipocyte and then esterified back into triglycerides for storage (Eckel 1989). Owing to its important role in lipid uptake, the abnormal activity of this enzyme has been suggested as a potential contributing factor in the pathogenesis of obesity (Gruen et al. 1978). Ramirez et al. (1997) demonstrated that abdominal adipose tissue LPL activity in sedentary obese men at their usual weight was significantly inversely correlated with plasma levels of bioavailable testosterone. In middle-aged men, an oral testosterone preparation caused a significant decrease in abdominal LPL activity when administered either in a single large dose or following a smaller four times daily dose for 6 weeks (Rebuffé-Scrive et al. 1991). Nine-month testosterone treatment of hypogonadal men has been reported to produce a marked decrease in both LPL activity and triglyceride uptake in subcutaneous abdominal adipose tissue (Márín et al. 1995). Following further investigation, the inhibition of lipid uptake after testosterone administration was more apparent in visceral than in abdominal subcutaneous adipose tissue (Márín et al. 1996). Thus, when testosterone is reduced, this promotes enhanced triglyceride storage in visceral depots.

Santosa & Jensen (2012) have recently investigated the chronic effects of testosterone deficiency on adipose tissue FA storage. Men with chronic hypogonadism induced by at least 6 months of ADT for the prevention of prostate carcinoma reoccurrence were compared to eugonadal control men matched for age and body composition. Results of the study showed that hypogonadal men stored a greater proportion of both dietary FA and FFA in lower body subcutaneous fat than did eugonadal men and that this was associated with increased expression of acyl-CoA synthetase (ACS (ACSS2)) from femoral adipose biopsies. Indeed, increased ACS suggests a potential for an accumulation of intracellular acylated FA. Acylated FA are additionally considered to act as signalling molecules, modulating other enzymes involved in FA metabolism such as ACC, AMP-activated kinase-kinase, HMG-CoA reductase, carnitine palmitoyl transferase and HSL (Knudsen et al. 1999). Castration of male mice resulted in an increase in mRNA expression of Fas and Acc in subcutaneous adipocytes and a non-significant increase in these lipogenic enzymes in intra-abdominal/perigonadal adipocytes (Macotela et al. 2009). Increases in subcutaneous Glut4 and intra-abdominal Glut1 (Slc2a4) were also observed, however, suggesting that while testosterone deficiency increased lipogenic capacity, it also increased insulin sensitivity.

Beneficial influence of testosterone on adipogenesis is also demonstrated in studies investigating the direct effects of testosterone on cultured stem cells. Singh et al. (2002) reported that the treatment of isolated mouse pluripotent stem cells with testosterone stimulated the development of cells of myocyte lineage rather than adipocytes and that testosterone deficiency promoted the development of
adipocytes over myocytes. Down-regulated expression of PPARγ, which controls adipogenic differentiation and lipid metabolism, was also reported at the mRNA and protein level. These effects on adipogenesis were blocked by the AR antagonist bicalutamide, suggesting AR-dependent mechanisms. Indeed, adipocytes are recognised to express ARs, the density of which is positively regulated by testosterone. More recently, however, Du et al. (2009) reported that a pre-inhibition of the AR did not influence the down-regulation of PPARγ activity by testosterone.

Testosterone influence on adipose glucose and lipid homoeostasis are shown to be directed, at least in part, via the AR. Male mice with a selective adipocyte AR knock-down (fARKO) displayed metabolic dysregulation with early insulin resistance/hyperinsulinaemia on normal chow diet and accelerated insulin deficiency, hyperglycaemia and visceral obesity on high-fat diet (McInnes et al. 2012). These effects were associated with altered expression of metabolic targets, although a degree of adipose depot specificity was apparent. Fas and adipose triglyceride lipase (ATGL) mRNA levels were elevated in subcutaneous adipose from fARKO mice compared with controls, but no difference was observed in perigonadal fat depots. Expression of HSL and LPL, however, was elevated in both subcutaneous and perigonadal adipose tissue of fARKO mice. Although Irs1 expression was not altered, IRS1 phosphorylation at the tyrosine residue as a measure of activation was significantly decreased in fARKO compared with wild-type mice, a mechanism potentially involving retinol-binding protein-4 (RBP4). Indeed, Rbp4 expression was selectively elevated in adipose tissue of fARKO mice (McInnes et al. 2012), supporting the hypothesis that elevated expression of Rbp4 may have an important role in lipid metabolism and insulin resistance (Graham et al. 2006, Ost et al. 2007). These AR-dependent mechanisms in adipose tissue may therefore contribute to glucose homoeostasis, and dysregulation of these pathways as a result of testosterone deficiency may contribute to the development of T2DM and MetS.

As mentioned previously, visceral fat is an active secretory tissue producing adipocytokines and other proinflammatory factors. In particular, proinflammatory adipocytokines IL1, IL6 and TNFα are increased in obesity with a downstream effect that stimulates liver production of CRP and other cytokine release (Schuster 2010). This chronic inflammation seen locally at the adipose tissue level also recruits monocytes that further contribute to the growing inflammatory activity. Overproduction of proinflammatory cytokines, other macrophage products and hormones by adipose tissue directly and indirectly induce insulin resistance (Kahn et al. 2006, Shoelson et al. 2006). In addition, adipokines are secreted into the circulation contributing to systemic and peripheral vascular inflammation and dysfunction associated with CVD (Guzik et al. 2006). As previously discussed, testosterone has several beneficial actions that decrease lipid deposition and therefore has the potential to reduce the release of adipocytokines by reducing fat tissue mass. Indeed, observational evidence suggests that IL1β, IL6, TNFα and CRP are inversely associated with serum testosterone levels in patients (Yang et al. 2005, Maggio et al. 2006, Kapoor et al. 2007a, Nettleship et al. 2007) and TRT has been reported to significantly reduce these proinflammatory mediators (Malkin et al. 2004b, Kalinchenko et al. 2010). RBP4, secreted by the adipose tissue, induces insulin resistance by reducing phosphatidylinositol-3-OH kinase signalling in the muscle, increasing the expression of phosphoenolpyruvate carboxykinase in the liver and local actions to inhibit tyrosine phosphorylation of IRS1 in adipose, along with diminished adiponectin and PPARγ (PPARA) activity typical for obesity (Yang et al. 2005). In a mouse model of selective fat tissue AR knockout (fARKO), Rbp4 mRNA expression was selectively increased in adipose tissue, along with an increased susceptibility to visceral obesity following high-fat diet feeding (McInnes et al. 2012). This suggests a role for AR in the metabolic actions of testosterone on fat accumulation and adipose tissue inflammatory response. McInnes et al. (2012) additionally demonstrated direct down-regulation of Rbp4 expression in the adipose-differentiated 3T3-L1 cells following treatment with non-aromatisable androgen. Su et al. (2009), however, showed elevated secretion of IL6 and MCP-1 in 3T3-L1 cells treated with testosterone, a mechanism that was dependent on NF-κB signalling.

Adiponectin and leptin are also two important adipokines that have been linked to T2DM and obesity. Unlike other adipose tissue-derived peptides that are elevated in obesity, adiponectin levels are decreased in obese individuals with insulin resistance, and higher levels of adiponectin are associated with lower risk of T2DM in older men and women (Krakoff et al. 2003, Spranger et al. 2003). Leptin levels are high in obese individuals and it has been suggested that resistance to leptin is one of the contributing factors to obesity and testosterone deficiency, as noted earlier in the hypogonadal-obesity–adipocytokine hypothesis (Jones 2007). Kapoor et al. (2007b) demonstrated that both leptin and adiponectin are reduced following biweekly testosterone propionate treatment for 3 months. Similarly, TRT was shown to lower serum adiponectin (Lanfranco et al. 2004, Page et al. 2006).
These interventional studies, however, were short-term and may reflect the reduction in total fat mass. Indeed, the reduction in these adipokines was correlated with a concomitant decrease in waist circumference (Kapoor et al. 2007b). The long-term effect of testosterone on adiponectin and leptin and the direct effects on adipokytokines remain unknown.

Consequently, testosterone treatment may have beneficial effects on preventing the pathogenesis of obesity by inhibiting adipogenesis, decreasing triglyceride uptake and storage, increasing lipolysis, influencing lipoprotein content and function and may directly reduce fat mass and increase muscle mass. This may, in turn, have a direct effect on circulating FA, the secretion of adipokytokines and subsequent insulin resistance. Some of these biochemical effects on lipid metabolism may be dependent on the location of the adipose depot and/or the tissue or cell type investigated. It is also worth noting that although the majority of studies report AR-dependent mechanisms, AR-independent effects in adipose tissue should not be discounted.

Conclusions

The high prevalence of clinical hypogonadism in men with T2DM and/or MetS has been shown in growing amounts of cross-sectional and epidemiological studies, and testosterone deficiency itself is a risk factor for the subsequent development of MetS and T2DM. Therefore, a bidirectional relationship between low testosterone with obesity and MetS is apparent. In parallel, the development of insulin resistance is multifaceted and involves multiple organs including liver, muscle and adipose tissue, which points to a heterogeneity among underlying mechanisms that could affect intervention strategies. This highlights the importance of taking multiple tissues into account and thus focussing on a systems biology approach. Early interventional studies suggest that TRT in hypogonal men with T2DM and/or MetS has beneficial effects on preventing the pathogenesis of obesity by inhibiting adipogenesis, decreasing triglyceride uptake and storage, increasing lipolysis, influencing lipoprotein content and function and may directly reduce fat mass and increase muscle mass. This may, in turn, have a direct effect on circulating FA, the secretion of adipokytokines and subsequent insulin resistance. Some of these biochemical effects on lipid metabolism may be dependent on the location of the adipose depot and/or the tissue or cell type investigated. It is also worth noting that although the majority of studies report AR-dependent mechanisms, AR-independent effects in adipose tissue should not be discounted.

Evidence that whole-body insulin sensitivity is reduced in testosterone deficiency and increases with testosterone replacement supports a key role of this hormone in glucose and lipid metabolism. These actions of testosterone are substantiated by demonstration of reported effects on fundamental and major biochemical regulators of glucose and lipid metabolism involved in insulin function. Furthermore, the different effects of testosterone in the major tissues involved in insulin sensitivity are consistent with the expected action of testosterone as an anabolic hormone. These underlying biochemical mechanisms of testosterone’s potential therapeutic benefit remain unclear and require further and fuller investigation to understand the tissue-specific actions of testosterone and the influence of AR-dependent and -independent pathways in metabolic regulation.

Declaration of interest

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

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