

# Estrogens and Body Weight Regulation in Men

Katya B. Rubinow

**Abstract** Our understanding of the metabolic roles of sex steroids in men has evolved substantially over recent decades. Whereas testosterone once was believed to contribute to metabolic risk in men, the importance of adequate androgen exposure for the maintenance of metabolic health has been demonstrated unequivocally. A growing body of evidence now also supports a critical role for estrogens in metabolic regulation in men. Recent data from clinical intervention studies indicate that estradiol may be a stronger determinant of adiposity than testosterone in men, and even short-term estradiol deprivation contributes to fat mass accrual. The following chapter will outline findings to date regarding the mechanisms, whereby estrogens contribute to the regulation of body weight and adiposity in men. It will present emergent clinical data as well as preclinical findings that reveal mechanistic insights into estrogen-mediated regulation of body composition. Findings in both males and females will be reviewed, to draw comparisons and to highlight knowledge gaps regarding estrogen action specifically in males. Finally, the clinical relevance of estrogen exposure in men will be discussed, particularly in the context of a rising global prevalence of obesity and expanding clinical use of sex steroid-based therapies in men.

## Introduction

Obesity has become a global epidemic. Overweight and obesity have an estimated global prevalence of over 2 billion people, surpassing that of undernutrition for the first time in history (Popkin et al. 2012). Although women are at higher risk for obesity than men, men are more likely to experience obesity-related disorders including insulin resistance, type 2 diabetes mellitus (T2DM), nonalcoholic fatty liver disease, and cardiovascular disease (Kautzky-Willer and Handisurya 2009). Thus, identifying risk factors for the development of obesity and its associated

---

K.B. Rubinow (✉)

Division of Metabolism, Endocrinology, and Nutrition Department of Medicine, University of Washington, Seattle, WA, USA

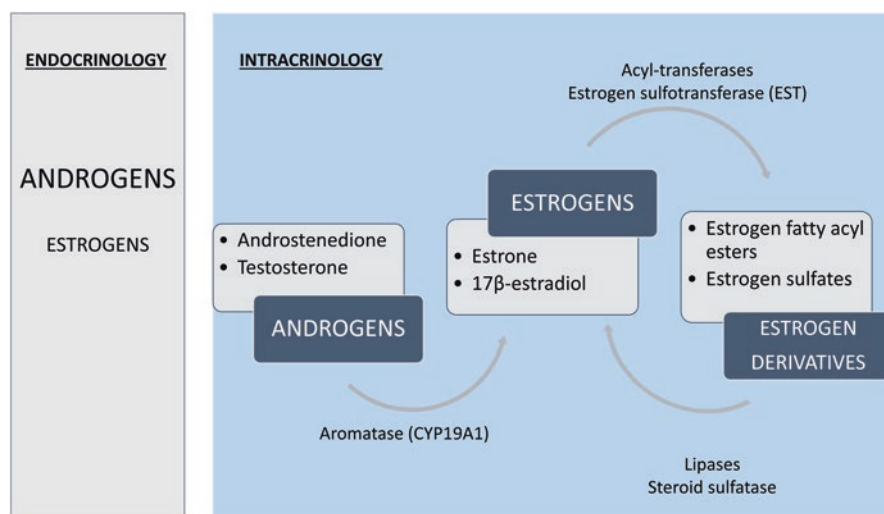
e-mail: [rubinow@uw.edu](mailto:rubinow@uw.edu)

complications specifically in men has been a growing area of interest. Over the past two decades, sex steroid deprivation in men has garnered increased attention as a key risk factor for metabolic disease. Thus, men with physiologic hypogonadism or those undergoing androgen deprivation treatment (ADT) for prostate cancer are at higher risk for the incident development of obesity and associated metabolic disorders including insulin resistance, nonalcoholic fatty liver disease, and T2DM (Ding et al. 2006; Hamilton et al. 2011; Keating et al. 2012). A contributory, causal role for testosterone deprivation in these metabolic disorders is supported by clinical data demonstrating that exogenous testosterone therapy reverses the increased adiposity evident in hypogonadal men and may improve insulin sensitivity in hypogonadal men with T2DM (Bhasin et al. 2003, 2010; Isidori et al. 2005; Jones et al. 2011).

Importantly, both clinical and preclinical data indicate that the beneficial metabolic effects of testosterone in men are not solely androgen mediated. Testosterone can undergo conversion to 17 $\beta$ -estradiol by the enzyme aromatase, and estradiol deficiency now appears a key facet of the metabolic risk conferred by either physiologic or iatrogenic hypogonadism. This recognition of the metabolic importance of estrogens in men was initially generated when rare syndromes of congenital estrogen deficiency in men were first reported about two decades ago (Jones et al. 2006). These clinical observations were followed by a succession of animal models demonstrating the critical, protective roles of estrogens in regulating body weight, adiposity, and glucose homeostasis in male as well as female mice. Notably, male mice with genetic deletion of estrogen receptor- $\alpha$  (ER $\alpha$ ) or aromatase exhibit a more pronounced phenotype of obesity and metabolic dysregulation than do male mice with disruption of androgen receptor (AR) signaling (Fan et al. 2005; Heine et al. 2000; Jones et al. 2000). These preclinical findings more recently have been corroborated by clinical intervention studies in men that have suggested a stronger effect of estradiol than testosterone in suppressing fat mass accrual in men. Greater understanding of the mechanisms by which estrogens regulate body weight and body composition in men is essential. These mechanistic insights will be critical for (1) formulating optimal strategies for sex steroid replacement in hypogonadal men, (2) avoiding potential harm of sex steroid-based interventions in clinical practice, and (3) developing novel interventions for the prevention and treatment of obesity in men.

## Estrogen Production and Metabolism

In men, ~15% of circulating estrogens derive directly from testicular production with the remainder generated from androgens through peripheral activity of the enzyme aromatase (Hemsell et al. 1974). The predominant form of circulating estrogen in men is 17 $\beta$ -estradiol, which is generated by aromatization of testosterone. Estrone is also found in circulation and formed from the aromatization of androstenedione. Estrogens can mediate effects through multiple pathways, with



**Fig. 1** Extensive regulation of estrogen production and metabolism within peripheral tissues is enabled by local expression of aromatase, which converts androgens to estrogens. Estrogens further can be converted to estrogen sulfates and estrogen fatty acyl esters through the activity of estrogen sulfotransferase and acyltransferases, respectively. Finally, these estrogen derivatives can be converted back to parent estrogens by steroid sulfatase and lipase activity

both genomic and non-genomic effects conferred through binding of its canonical receptors ER $\alpha$  and ER $\beta$ . Estrogens also can signal through a membrane-bound G-protein-coupled receptor (GPER). Further, ER $\alpha$  and ER $\beta$  can mediate both genomic and non-genomic ligand-independent effects (Foryst-Ludwig and Kintscher 2010). Of note, all three receptors have been implicated in the regulation of body weight and adiposity in both males and females (Cooke et al. 2001; Davis et al. 2014; Heine et al. 2000). Adipose tissue in particular is rich in estrogens and other sex steroids, with markedly higher concentrations of both estrogens and androgens than are found in serum (Deslypere et al. 1985).

Importantly, circulating estrogen levels are not the sole determinant of tissue estrogen levels, highlighting the distinction between endocrinology (hormones released into circulation) and intracrinology, the cell-specific regulation of sex steroid metabolism (Fig. 1). Indeed, several clinical studies have demonstrated dissociations between circulating and intra-adipose estrogen levels, including studies with male subjects (Blankenstein et al. 1992; Bélanger et al. 2006; Deslypere et al. 1985; Wang et al. 2013). Aromatase is expressed broadly throughout central and peripheral tissues including brain and adipose tissue and skeletal muscle; therefore, through local aromatase activity in key metabolic tissues, estrogen production is regulated in tissue-specific fashion (Matsumine et al. 1986; Simpson 2004). Estrogen metabolism also is locally regulated, predominantly through the enzyme estrogen sulfotransferase (EST), which inactivates 17 $\beta$ -estradiol through sulfoconjugation.

Estrogens alternatively can undergo conversion to fatty acyl esters mediated by acyl-transferases. Estrogen fatty acyl esters are found in both serum and peripheral tissues, as are estrogen sulfates. Further, estrogen fatty acyl esters and estrogen sulfates can undergo conversion to their bioactive counterparts through lipase and steroid sulfatase activity, respectively. Adipose tissue is particularly enriched in estrogen fatty acyl esters and consequently has an extensive buffering system that enables local regulation of estrogen production and metabolism. Notably, in a study of obese men, 17 $\beta$ -estradiol fatty acyl ester concentrations did correlate in serum and fat (Wang et al. 2013), possibly indicating that serum estrogen levels influence stored estrogen content in adipose tissue, but conversion to bioactive forms is locally regulated. These findings highlight the limitations of circulating levels as an index of tissue-specific estrogen regulation and underscore the need to carefully delineate tissue-specific pathways of estrogen metabolism and signaling in order to fully define estrogen-mediated mechanisms of body weight regulation in men.

## Genetic Mutations in Men and Mice

In the 1990s, an initial series of cases were published detailing men with rare genetic mutations in the genes encoding aromatase or ER $\alpha$  that led to partial or complete loss of estrogen signaling (Carani et al. 1997; Morishima et al. 1995; Simpson 1998; Smith et al. 1994). Although initially reported as predominantly a skeletal phenotype, congenital estrogen deficiency soon was identified as a syndrome of metabolic perturbations characterized by increased central adiposity, insulin resistance, and nonalcoholic fatty liver disease (Maffei et al. 2007). Further, in the case of aromatase deficiency, these metabolic disturbances could be reversed with exogenous estradiol but not testosterone treatment (Maffei et al. 2007).

The development of genetically modified mice used to model estrogen deficiency provided further, compelling evidence of the metabolic importance of estrogen signaling in males. These preclinical models also provided new insights into the mechanisms whereby estrogens contribute to energy balance and body weight regulation in male as well as female mice. Thus, a striking metabolic phenotype first was observed for both male and female mice with global ER $\alpha$  deficiency. ER $\alpha$ -deficient male mice exhibited increased adiposity that became more pronounced with age, such that older mice had more than double the white adipose tissue mass of wild-type controls without differences in brown fat mass (Cooke et al. 2001; Heine et al. 2000; Ohlsson et al. 2000). This phenotype was ascribed to reduced energy expenditure in ER $\alpha$ -deficient mice rather than differential food intake (Heine et al. 2000). Male mice with adipocyte-specific ER $\alpha$  deficiency similarly exhibited significant increases in white adipose tissue mass, suggesting that loss of ER $\alpha$  signaling specifically within adipose tissue leads to changes in energy metabolism that favor increased adiposity.

In contrast to models of ER $\alpha$  deficiency, male mice with global ER $\beta$  deficiency exhibited comparable body weight and insulin sensitivity to wild-type mice on a

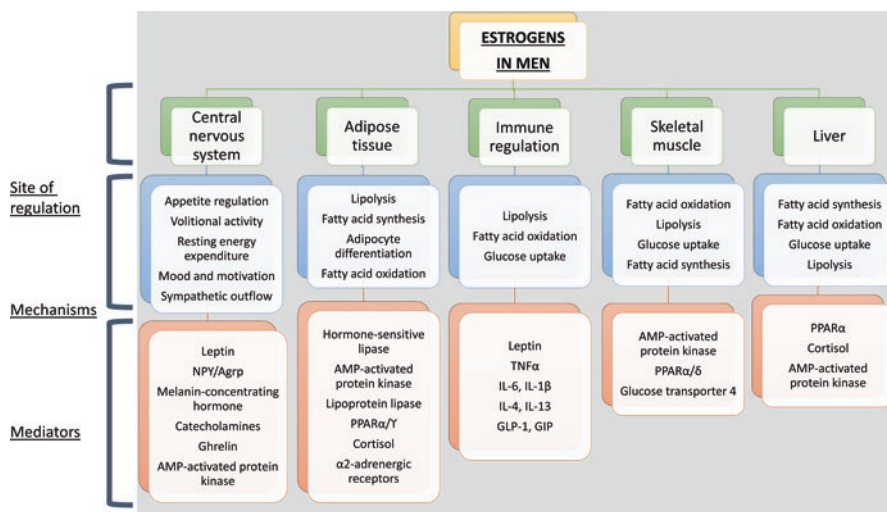
chow diet (Ohlsson et al. 2000). When female ER $\beta$ -deficient mice were exposed to a high-fat diet, however, they exhibited greater adiposity but less insulin resistance than wild-type controls, a phenotype that was ascribed to enhanced PPAR $\gamma$  activation (Foryst-Ludwig et al. 2008). To date, a parallel interaction between high-fat feeding and ER $\beta$  deficiency has not been established for male mice.

Similar to male mice with abrogated ER $\alpha$  signaling, male mice with aromatase deficiency were shown to exhibit increased adiposity (Jones et al. 2001). In these mice, increased fat mass was attributable to reductions in spontaneous physical activity and glucose oxidation and found in association with insulin resistance and hepatic steatosis (Jones et al. 2000; Takeda et al. 2003). Liver from aromatase-deficient male mice showed increased expression of genes involved in fatty acid synthesis, and steatosis was reversed with administration of either 17 $\beta$ -estradiol or an ER $\alpha$  but not ER $\beta$  agonist (Cooke et al. 2001). In a second model of male mice with aromatase deficiency, hyperglycemia was attributed specifically to hepatic insulin resistance and increased gluconeogenesis (Van Sinderen et al. 2014). This liver phenotype again was reversed with exogenous estradiol. In female aromatase-deficient mice, adipose tissue exhibited increased expression of lipoprotein lipase (LpI), consistent with increased fatty acid uptake, though this finding has not yet been corroborated in male mice (Misso et al. 2003).

More recently, potential metabolic roles of the membrane estrogen receptor GPER (GPR30) have been supported through genetic models. Male mice with global GPER deficiency showed greater body weight and fat mass accrual than wild-type controls. Increased adiposity was found in association with greater adipocyte size and ascribed to reduced energy expenditure rather than differential food intake (Davis et al. 2014). Notably, obesity due to GPER deficiency evolved earlier in male than female mice (Davis et al. 2014).

## Central Mechanisms of Estrogen-Mediated Body Weight Regulation

Estrogens could regulate body weight in men through numerous mechanisms in both central and peripheral tissues (Fig. 2). Extensive work has demonstrated that central estradiol signaling plays key roles in the regulation of appetite, energy expenditure, and body weight (Brown and Clegg 2010; Mauvais-Jarvis et al. 2013). Aromatase is broadly expressed in the brain, but expression is particularly enriched in the hypothalamus, the principal regulatory site of appetite and energy expenditure as well as reproductive behavior (Abdelgadir et al. 1994; Roselli et al. 2009). The hypothalamus also has abundant ER expression, particularly in the arcuate, paraventricular, and ventromedial nuclei, with ER $\alpha$  expression generally higher than ER $\beta$  (Brown and Clegg 2010; Merchenthaler et al. 2004; Simerly et al. 1990). The central nervous system further is a site of de novo estrogen generation, as



**Fig. 2** Estrogens influence body weight and body composition in men through myriad pathways in key metabolic tissues

astrocytes and neurons have all the requisite enzymes to synthesize estradiol from cholesterol (Gillies and McArthur 2010).

Estradiol is well recognized as a critical regulator of both food intake and energy expenditure in females, with extensive research demonstrating its signaling effects particularly in the arcuate and ventromedial nuclei of the hypothalamus (Mauvais-Jarvis et al. 2013). Although most work to date has focused on the central mechanisms whereby estradiol regulates body weight in females, considerable evidence supports a parallel role for estradiol in males, as well. Aromatase expression in most brain regions is comparable in men and women (Stoffel-Wagner et al. 1999), and hypothalamic ER expression is comparable in male and female rodents, including within both the arcuate and paraventricular nuclei (Brown et al. 1992; Chakraborty et al. 2008).

Preclinical findings in males suggest an interaction between central estradiol and leptin signaling, as has been well established in females. The anorexigenic effects of leptin are more pronounced in females than in males, a phenomenon that has been ascribed to estradiol-mediated sensitization to leptin signaling. Supporting this idea, intact male rats did not exhibit changes in food intake after central leptin administration. However, a significant reduction in food intake after leptin administration was evident in orchietomized male rats treated with subcutaneous estradiol (Clegg et al. 2006). Although increased leptin sensitivity was seen in males only with pharmacological estradiol treatment, these observations do not exclude a leptin-sensitizing effect of estradiol at physiological levels in males; thus, additional

work is needed to determine whether diminished leptin sensitivity is found in males with selective estradiol deprivation. Further supporting a dynamic interaction between estradiol and leptin in males, both males and females exhibited ER $\alpha$  upregulation in the arcuate nucleus of the hypothalamus in the setting of leptin deficiency (Chakraborty et al. 2008). Importantly, leptin is a critical regulator not only of energy intake but also energy expenditure. Thus, leptin also increases energy expenditure, in part through enhanced activity of the sympathetic nervous system (Morton and Schwartz 2011).

However, the anorexigenic effects of estradiol in males clearly are not mediated solely through leptin, as genetically leptin-deficient obese male mice exhibited diminished food intake and body weight loss after estradiol treatment (Gao et al. 2007). This phenomenon was ascribed to estradiol-mediated stimulation of POMC neurons in the arcuate nucleus through a leptin-independent, ER $\alpha$ -STAT3 pathway. The anorexigenic effects of supraphysiologic estradiol administration in males have been ascribed to other pathways, as well. Thus, in male rats, reductions in food intake after estradiol treatment were thought to be due in part to inhibition of the orexigenic neuropeptide melanin-concentrating hormone (MCH) (Mystkowski et al. 2000). Estradiol-mediated regulation of MCH may reflect an indirect interaction; although ER $\alpha$  did not co-localize with MCH neurons in male rats, both neuronal populations were found in abundance within the lateral hypothalamic area (Muschamp and Hull 2007). Nonetheless, estradiol-induced hypophagia has been observed in both MCH- and leptin-deficient male mice, and the hypophagic effect became more pronounced when mice were exposed to a high-fat diet (Tritos et al. 2004). Additional postulated effects of estradiol-mediated hypophagia in males include regulation of cannabinoid and ghrelin signaling. Thus, estradiol has been shown to downregulate cannabinoid receptor expression in the hypothalamus and attenuate cannabinoid-induced hyperphagia (Kellert et al. 2009; Riebe et al. 2010). Further, 17 $\beta$ -estradiol was found to inhibit the hyperphagic effect of central administration of the orexigenic hormone ghrelin in male rats (Clegg et al. 2007).

Notably, animal data do not uniformly demonstrate that estradiol-mediated effects on appetite regulation are similar in males and females with comparable degrees of estradiol exposure. A clear sexual dimorphism in hypothalamic estradiol signaling was illustrated by an experimental model that examined in parallel female sheep and castrated male sheep administered exogenous estradiol. Females and estradiol-supplemented males showed pronounced differences in the expression of hypothalamic genes implicated in appetite regulation in response to both light cycle and food restriction (Archer et al. 2004). A sexual dimorphism in the role of hypothalamic ER $\alpha$  signaling also has been demonstrated in mice, as ER $\alpha$  silencing in the ventromedial nucleus of the hypothalamus led to body weight gain in female but not male mice (Frank et al. 2014). Similarly, knockdown of ER $\alpha$  in POMC neurons in the arcuate nucleus of the hypothalamus promoted increased food intake and body weight gain exclusively in female mice (Xu et al. 2011).

In addition to the direct regulation of appetite through hypothalamic signaling, estradiol also could mediate changes in energy balance through indirect effects on



mood and motivation in men. Thus, these affective effects could produce changes in appetite and volitional activity that influence overall energy balance and, consequently, body weight. In male rats subject to orchiectomy, testosterone replacement conferred changes in behavior indicative of antianxiety and antidepressant effects, but these behavioral changes were abrogated with concurrent administration of an aromatase inhibitor (Carrier et al. 2015). Lower serum 17 $\beta$ -estradiol levels correlated with more depressive symptoms in a cohort of older men (Castanho et al. 2014), as well as in a population of men with obesity (Monteagudo et al. 2016).

Interestingly, in male mice fed a diet high in phytoestrogens, decreased adiposity was found despite increased food intake (Cederroth et al. 2007). This phenotype was ascribed in part to increased voluntary activity and resting energy expenditure consequent to changes in hypothalamic neuropeptides. Hypothalamic gene expression was notable for increased mRNA expression of the orexigenic orexin A and MCH but reduced mRNA expression of agouti-related peptide (Agrp) (Cederroth et al. 2007). Whereas increases in orexin A and MCH expression were thought to underlie the increased food intake in these animals, increased basal metabolic rate, lipid oxidation, and volitional activity were ascribed to reduced Agrp expression. Of note, in immortalized hypothalamic neurons treated with 17 $\beta$ -estradiol, ER $\alpha$ -mediated signaling reduced whereas ER $\beta$ -mediated signaling augmented Agrp expression (Titolo et al. 2006). An ER $\alpha$ -dependent increase in voluntary activity manifest as wheel running also was seen in male mice subject to orchiectomy followed by estradiol treatment (Ogawa et al. 2003).

Thus, findings to date support a role for central estradiol signaling in the regulation of appetite and energy expenditure in males. However, most findings are predicated on models that expose males to supraphysiologic doses of exogenous estradiol. These models underscore the importance of not viewing males simply as estrogen-deficient females and the corresponding need for continued investigation of physiologic estrogen signaling specifically in males. Indeed, some experimental models argue against a potent role for estradiol in appetite regulation at physiologic levels in males. Thus, additional work is necessary to better discriminate between concentration-dependent effects and true sexual dimorphisms in centrally mediated effects of estradiol in body weight regulation.

## **Adipose-Specific Mechanisms of Estrogen-Mediated Body Weight Regulation**

Among peripheral metabolic tissues, adipose tissue is particularly enriched in both aromatase and ER expression. Adipose tissue aromatase is found predominantly in preadipocytes and is part of the pro-adipogenic program coordinated by glucocorticoid signaling (Simpson 2004). Similar to the CNS, adipose tissue generally exhibits higher expression of ER $\alpha$  than ER $\beta$ , and expression levels are comparable in men and women (Pedersen et al. 2001). ER $\alpha$  has been identified in both mature



adipocytes and preadipocytes, whereas ER $\beta$  was found exclusively in mature adipocytes (Dieudonné et al. 2004). The regulation of ER in adipose tissue is partially dependent on estradiol and exhibits both cell type specificity and sexual dimorphisms. Whereas 17 $\beta$ -estradiol upregulated expression of both ER $\alpha$  and ER $\beta$  in adipocytes harvested from women, it selectively upregulated ER $\alpha$  expression in adipocytes from men (Dieudonné et al. 2004). Further, ER $\alpha$  expression in preadipocytes was not estradiol-responsive in cells from either sex.

Preclinical and clinical data collectively support an overall anti-obesogenic role for estradiol action in adipose tissue. Fat mass accrual occurs through adipocyte hypertrophy as well as adipocyte hyperplasia, the generation of new adipocytes through preadipocyte differentiation. Adipocyte hypertrophy results from progressive accumulation of lipid within the cell, either through lipogenesis or uptake of extracellular lipid. One described mechanism by which estradiol can suppress adiposity is inhibition of Lpl, which hydrolyzes triglycerides and thereby releases free fatty acids for cellular uptake. Estradiol has been shown to inhibit Lpl activity in women and suppress Lpl expression in cultured 3T3-L1 cells, an immortalized cell line that can be induced to differentiate into cells that phenotypically resemble adipocytes (Homma et al. 2000; Price et al. 1998). Increased Lpl-mediated fatty acid uptake also has been proposed as a primary mechanism underlying the increased adiposity seen in aromatase-deficient mice though this was proposed on findings limited to female mice (Misso et al. 2003). Illustrating the dose dependency of estrogen-mediated effects, high-dose estradiol treatment inhibited Lpl protein expression in adipocytes isolated from women, whereas the lowest treatment dose enhanced Lpl expression (Palin et al. 2003). Again, however, parallel dose-dependent responses in adipocytes harvested from men have not been determined.

Although orchietomy has been used extensively in rodent studies to investigate the metabolic effects of gonadal steroids in males, few studies to date have carefully discriminated between androgen- and estrogen-mediated outcomes. In a recent study, male mice were subject to orchietomy with testosterone replacement with or without an aromatase inhibitor. Orchietomy led to increases in adiposity in conjunction with increased adipose tissue expression of Lpl and the lipogenic genes fatty acid synthase and sterol regulatory element-binding protein-1 (SREBP-1). These changes in both fat mass and gene expression were fully reversed by testosterone replacement (Holland et al. 2016). Adipose tissue expression of Lpl and fatty acid synthase appeared at least partially suppressed by estrogen exposure, whereas SREBP-1 expression exhibited more pronounced estrogen-mediated inhibition. Thus, treatment with testosterone and an aromatase inhibitor led to an intermediate phenotype, with less adiposity than seen in orchietomized animals but persistent increases in fat mass and lipogenic gene expression relative to animals administered testosterone replacement alone (Holland et al. 2016). Diminished expression of lipogenic genes regulated by SREBP-1 also was seen *in vitro* in cultured murine adipocytes treated with 17 $\beta$ -estradiol (D'Eon et al. 2005). Further supporting an anti-obesogenic role for estrogen in males, male mice fed a diet enriched in phytoestrogens exhibited reduced adiposity, with enhanced AMP-activated protein

kinase (AMPK) signaling in adipose tissue (Cederroth et al. 2008). As AMPK promotes fatty acid  $\beta$ -oxidation and suppresses lipogenesis, its regulation by estrogens may be another mechanism whereby estrogen favors lipid utilization over lipid uptake, synthesis, and storage. Collectively, these preclinical findings indicate that adequate androgen and estrogen exposure are likely both required to restrain adiposity in males.

Estradiol signaling in males has been shown to contribute to the regulation of preadipocyte proliferation and differentiation, central facets of fat mass accrual. Again, sexual dimorphisms are evident in the effects of estradiol on adipogenesis. Thus,  $17\beta$ -estradiol increased preadipocyte proliferation and enhanced differentiation in cells harvested from female but not male rats. In mature adipocytes from rats of both sexes, however, estradiol treatment upregulated expression of PPAR $\gamma$ , the central transcriptional regulator of adipocyte differentiation (Dieudonne et al. 2000). In a clinical study,  $17\beta$ -estradiol increased proliferation of preadipocytes harvested from both men and women, although the rate of proliferation was significantly faster in preadipocytes from women (Anderson et al. 2001). One mechanism underlying estradiol's role in adipogenesis may be regulation of glucocorticoid metabolism. Although glucocorticoids induce aromatase expression and estrogen production during preadipocyte differentiation, this may reflect a key role for estradiol in the restraint of adipogenesis through negative feedback regulation of glucocorticoid signaling. Thus, in male mice, exogenous  $17\beta$ -estradiol administration reduced body weight gain in a model of diet-induced obesity. This lower adiposity occurred in association with reduced adipose tissue mRNA expression and activity of  $11\beta$ -hydroxysteroid dehydrogenase type 1 ( $11\beta$ -HSD1), the enzyme that generates cortisol from cortisone (Dakin et al. 2015). These findings led the authors to propose that inhibition of cortisol generation and its associated pro-adipogenic effects is a primary mechanism through which estradiol suppresses fat accrual in males (Dakin et al. 2015). Supporting this conclusion, treatment with  $17\beta$ -estradiol rapidly inhibited  $11\beta$ -HSD activity in cultured 3T3-L1 adipocytes; interestingly, this effect did not appear dependent on ER signaling (Tagawa et al. 2009).

Estradiol further has been implicated in the regulation of adipocyte lipolysis, another mechanism by which it can serve as a critical determinant of the balance between lipid storage and mobilization. Both pro- and anti-lipolytic roles for estradiol have been reported. Thus, upregulation of  $\alpha 2$ -adrenergic receptors was found after estradiol treatment of subcutaneous adipocytes from women, suggesting inhibition of lipolysis (Pedersen et al. 2004). In apparent contrast, however,  $17\beta$ -estradiol treatment amplified catecholamine-induced lipolysis in murine adipocytes (D'Eon et al. 2005). Consistent with both seemingly discordant findings, testosterone treatment was shown to simultaneously upregulate both  $\beta$ - and  $\alpha 2$ -adrenergic receptors in adipocytes harvested from castrated male hamsters (Giudicelli et al. 1993). Whether these respective effects were androgen or estrogen dependent was not established. In subcutaneous adipocytes isolated from women, estradiol also was shown to exert pro-lipolytic effects through dose-dependent stimulation of hormone-sensitive lipase (Palin et al. 2003). It remains to be established whether estradiol confers similar effects in adipocytes isolated from men.

Estrogen concentrations are regulated within adipose tissue not only through local production by aromatase but also estrogen metabolism mediated primarily by EST. The role of EST in body weight and fat mass regulation has been examined, and interestingly, EST exhibits sexually dimorphic expression and may exert divergent effects on adipogenesis in rodents and humans. EST expression was identified in white adipose tissue from male but not female rodents, and EST deficiency in male mice led to increases in epididymal fat mass with larger adipocyte size (Khor et al. 2008). These findings are consistent with *in vitro* data demonstrating that EST expression declined with the differentiation of both 3T3-L1 cells and primary mouse adipocytes, whereas EST overexpression inhibited 3T3-L1 cell differentiation (Wada et al. 2011). In humans, EST expression initially was detected in subcutaneous adipose tissue from obese men and women and subsequently in adipose tissue from nonobese women, as well (Ahima et al. 2011; Ihunnah et al. 2014). In striking contrast to preclinical findings, EST overexpression in human adipose tissue stem cells promoted adipocyte differentiation in association with increased expression of lipogenic genes, whereas differentiation was inhibited by EST knock-down. Further, these effects were shown to be ER dependent, indicating that they were conferred specifically through the enzymatic activity of EST that leads to inactivation of estradiol (Ihunnah et al. 2014). The authors also showed a positive correlation between adipose tissue EST expression and BMI. Critically, however, these findings were generated with adipose stem cells isolated exclusively from women and need corroboration in men, as well.

## Other Peripheral Mechanisms of Estrogen-Mediated Body Weight Regulation

Although aromatase and ER expression are particularly enriched in adipose tissue, estrogen signaling in other peripheral metabolic tissues also may make a significant contribution to estrogen-mediated regulation of energy metabolism and body weight. In female mice, estradiol was found to downregulate expression of lipogenic genes in both skeletal muscle and liver. Further, estradiol increased activation of AMPK and PPAR $\delta$  in skeletal muscle, putative mechanisms through which estradiol appeared to cause a shift away from lipid storage and toward fatty acid oxidation (D'Eon et al. 2005). ER $\alpha$  deficiency in skeletal muscle led to increases in gonadal fat mass and impaired glucose tolerance in female mice, findings ascribed to dysregulated mitochondrial turnover and function (Ribas et al. 2016). Both ER $\alpha$  and ER $\beta$  have been shown to regulate glucose transporter 4 (GLUT4) expression in skeletal muscle as well as adipose tissue in male mice with divergent effects of the two receptor subtypes; GLUT4 expression is upregulated by ER $\alpha$  but downregulated by ER $\beta$  (Barros et al. 2006, 2009). Although the ER $\alpha$ -mediated increase in GLUT4 expression may be seen as beneficial with regard to enhanced glucose

disposal, it nonetheless also contributes to increased energy uptake in adipocytes that could manifest as fat mass accrual in the setting of positive energy balance.

An emergent area of research involves the roles of sex steroids in regulating intestinal flora. The composition of the gut microbiome has received substantial attention as a potential contributor to obesity and associated metabolic dysregulation (Khan et al. 2016). A recent mouse model offers initial evidence that sex steroid exposure may influence the composition of the gut microbiome. Thus, in male mice fed a high-fat diet, castration led to increases in visceral adiposity in association with alterations in intestinal microflora (Harada et al. 2016). Further, castration-induced increases in visceral fat were blocked with antibiotic administration. Importantly, changes in the intestinal microflora were not seen on a regular chow diet, suggesting these changes may reflect not a direct, sex steroid-mediated effect but rather an interaction between sex steroids and diet and/or excess energy intake. Further, this study did not discriminate between androgen- and estrogen-mediated effects on intestinal flora. Clinical data regarding sex steroids and the gut microbiome are scant. In a cross-sectional study that included healthy men, urinary estrogen levels exhibited a strong, positive correlation with diversity in intestinal flora and fecal  $\beta$ -glucuronidase activity, leading the authors to posit that the gut microbiome may regulate circulating estrogen levels (Flores et al. 2012). The possibility exists, too, that this relationship may be inverse or bidirectional. Thus, estrogen signaling in these extra-adipose sites of energy metabolism could also contribute to estrogen-mediated changes in energy balance, body weight, and adiposity in males. Critically, however, estrogens mediate dose-, context-, and sex-dependent roles, and additional work is therefore necessary to establish and characterize these estrogen-mediated effects specifically in males.

## The Immunomodulatory Effects of Estradiol

A growing area of research is focused on defining how the immunomodulatory effects of estradiol might contribute to estrogen-mediated regulation of energy balance and body composition. Estradiol is known to influence immune cell function, with extensively described effects on cellular differentiation, phenotype, and function in both adaptive and innate immunity (Cunningham and Gilkeson 2011; Kovats 2012, 2015). Resident immune cells are present within adipose tissue and undergo dynamic changes in both number and phenotype during states of both positive and negative energy balance with associated adipose tissue remodeling (Gerriets and MacIver 2014; Mathis 2013; Olefsky and Glass 2010; Suganami and Ogawa 2010; Weisberg et al. 2003). Animal models demonstrate that adipose tissue immune cells – through the secretion of paracrine effectors including growth and angiogenic factors, matrix metalloproteinases, and cytokines – are critical mediators of lipid and glucose metabolism, adipocyte differentiation, and tissue remodeling (Lacasa et al. 2007; Lu et al. 2010; Lumeng et al. 2008; Spencer et al. 2010; Suganami and Ogawa 2010; Xu et al. 2003; Ye and McGuinness 2013).

Estradiol-mediated effects on immune function are highly context dependent and vary as a function of estradiol concentration and timing of exposure, the distinct microenvironment and concurrent signals, and target cell type (Straub 2007). Irrespective of the context-dependent magnitude and directionality of these estradiol-mediated effects, however, estradiol has been reproducibly shown to modulate cellular differentiation, survival, and chemokine and cytokine production in both lymphocytes and myeloid cells. Most of estradiol's immunomodulatory effects are thought to be mediated through ER $\alpha$  signaling, but ER $\beta$  and GPER also have been implicated in estradiol-mediated effects on immune cell function (Blasko et al. 2009; Monteiro et al. 2014; Straub 2007).

The regulation of cytokine secretion constitutes one general mechanism whereby estradiol can mediate indirect effects on energy metabolism, insulin sensitivity, and adipogenesis. Estradiol has been shown to regulate production of the predominantly macrophage-derived cytokines TNF $\alpha$ , IL-1 $\beta$ , and IL-6, with either stimulatory or inhibitory effects on secretion that depend largely on macrophage activation state. In general, at higher concentrations, these cytokines exert inhibitory effects on adipocyte differentiation and fatty acid synthesis while promoting lipolysis. Importantly, however, immune-derived mediators play complex roles in metabolic regulation and defy simple designation as good or bad for metabolic health (Wang and Ye 2015; Ye and McGuinness 2013). TNF $\alpha$  illustrates this principal, as its common designation as a “pro-inflammatory” or insulin resistance-promoting cytokine fails to capture the complexity and context dependence of its metabolic effects. Thus, the effects of TNF $\alpha$  exposure on GLUT4 expression and insulin signaling in adipocytes varied as a function of time and TNF dose (Stephens et al. 1997). Elevated circulating levels of TNF $\alpha$  were found in aromatase-deficient mice and thought to play a pathogenic role in the metabolic dysregulation conferred by aromatase deficiency. Strikingly, however, when TNF receptor type 1 (TNFR1) was knocked down in these mice, hepatic steatosis and insulin resistance not only failed to improve but rather were further exacerbated (Toda et al. 2010).

Estradiol-regulated cytokines other than TNF also appear to have significant metabolic roles. Evidence from both rodents and humans supports a role for IL-6 in promoting the secretion of glucagon-like peptide-1 (GLP-1), a gut-derived hormone that regulates satiety and glucose homeostasis (Kahles et al. 2014; Lebherz et al. 2016). The cytokines IL-4 and IL-13 have been implicated in the regulation of adipose tissue energy metabolism, as both were shown to increase expression of uncoupling protein 1 (UCP1) and thermogenic capacity in adipocytes (Qiu et al. 2014). Thus, through regulation of cytokine secretion alone, estradiol could mediate changes in adipocyte differentiation and energy metabolism that could substantially impact fat mass accrual. Moreover, in addition to direct effects on immune cell phenotype and function, estradiol also could modulate immune activity indirectly, through pathways involving leptin, glucocorticoids, or sympathetic nervous system function, all of which are regulated by 17 $\beta$ -estradiol and, in turn, influence immune cell function.

Findings in female mice further lend *in vivo* evidence that estradiol regulates adiposity and energy metabolism through immunomodulatory effects. Thus, ovari-

ectomy resulted in altered cytokine expression and immune cell populations in adipose tissue (Rogers et al. 2009). Lending more direct evidence to this proposed model, female mice were generated with selective ER $\alpha$  deficiency in either myeloid or all hematopoietic cells. In both models, ER $\alpha$  deficiency conferred significant increases in fat mass (Ribas et al. 2011). In mice with myeloid-specific ER $\alpha$  deficiency, increased fat mass was found in association with increased adipocyte size and greater tissue macrophage infiltration (Ribas et al. 2011). Thus, these findings indicate that the immunomodulatory effects of estradiol are at least partially responsible for the obesity and associated metabolic derangements seen in mice with global ER $\alpha$  deficiency. To date, however, parallel studies have not been performed in male mice.

## Estrogens Beyond 17 $\beta$ -Estradiol: Estrone and 17 $\alpha$ -Estradiol

Although 17 $\beta$ -estradiol is the predominant circulating estrogen in men and premenopausal women, it may not be the only relevant estrogen with regard to metabolic regulation in men. Among men enrolled in the Diabetes Prevention Program, positive associations were found between serum estrone concentrations and the incident development of T2DM (Mather et al. 2015). Another study similarly found that circulating estrone levels are associated with incident development of T2DM in men and, further, are a better predictor of diabetes development than serum estradiol levels (Jasuja et al. 2013b). Changes in serum estrone levels were shown to positively correlate with BMI, and increased prevalence of both diabetes and cardiovascular disease was found among men in the highest quintile of serum estrone levels (Jasuja et al. 2013a). Other studies have corroborated this positive association between body weight and serum estrone levels in obese men (Bélanger et al. 2006; Kley et al. 1980a, b).

This reproducible association between serum estrogen levels and adiposity in men has been ascribed to increased adipose tissue aromatase activity in the setting of fat mass accumulation (Brind et al. 1990). Rather than merely a marker of adipose tissue aromatase activity, however, estrone could mediate metabolic effects. Thus, both estrone and its fatty acyl ester oleoyl-estrone have been shown to influence body weight and adiposity in rodents as well as adipogenesis in *in vitro* models. Administration of oleoyl-estrone to female rats reduced fat mass through both decreases in food intake and enhanced lipolysis and fat oxidation (Sanchis et al. 1996, 1997). Similarly, oleoyl-estrone decreased food intake in male Zucker rats and produced even more marked loss of fat mass than seen in female rats (Grasa et al. 2001). The anti-adiposity effects of oleoyl-estrone were abrogated with corticosteroid treatment, suggesting inhibition of glucocorticoid signaling may be a key mechanism through which oleoyl-estrone reduces fat mass (Serrano et al. 2009). In contrast, however, elevated estrone exposure has been posited to contribute directly to increases in body weight and adiposity (Remesar et al. 1999). In acute food deprivation in rats, serum estrone levels rose whereas estrone fatty esters declined, find-



ings potentially consistent with their respective putative effects on energy conservation and utilization (Vilà et al. 1999).

Another estrogen that has been implicated in metabolic regulation is 17 $\alpha$ -estradiol. A naturally occurring enantiomer of 17 $\beta$ -estradiol, 17 $\alpha$ -estradiol is best described as a paracrine regulator in brain (Toran-Allerand et al. 2005) but more recently was found to play roles in body weight regulation and energy homeostasis. In male mice, systemic administration of 17 $\alpha$ -estradiol led to reductions in adiposity greater than those seen with modest caloric restriction, with particular loss of visceral adipose tissue (Stout et al. 2017). Both central and peripheral mechanisms of action were supported. Thus, 17 $\alpha$ -estradiol-treated mice exhibited lower food intake with associated changes in the expression of hypothalamic genes implicated in appetite regulation, and 3T3-L1 adipocytes showed changes in energy-sensing pathways after 17 $\alpha$ -estradiol treatment in vitro. Male mice treated with 17 $\alpha$ -estradiol further showed increased AMPK activation in adipose tissue but not liver or skeletal muscle (Stout et al. 2017). The regulation of 17 $\alpha$ -estradiol production has not been elucidated, but its local production is indicated by persistent presence throughout the brain after gonadectomy and/or adrenalectomy in mice (Toran-Allerand et al. 2005). Thus, estrone and 17 $\alpha$ -estradiol underscore the complexity of local estrogen metabolism. Careful, tissue-specific interrogation of an expanded scope of estrogens and their derivatives will therefore be essential to fully delineate the estrogen-mediated mechanisms of body weight regulation in men.

## Estrogen and Obesity in Men: Too Much or Too Little?

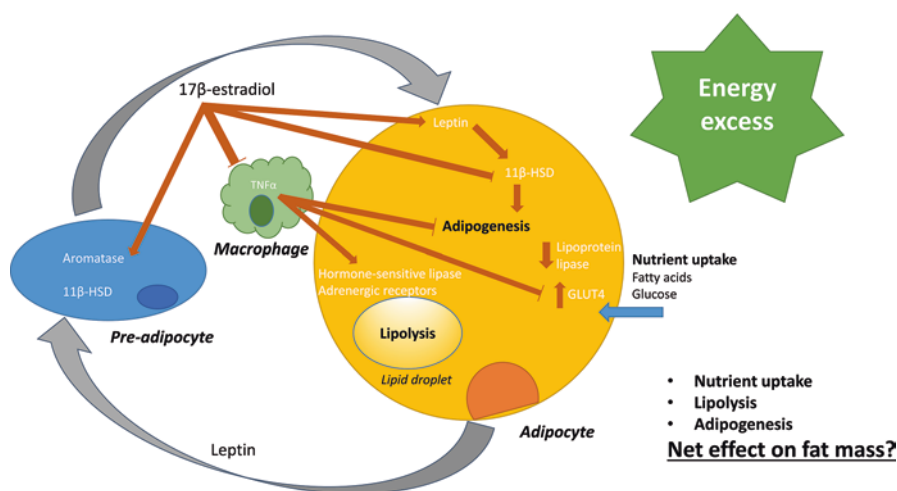
Estradiol deficiency clearly predisposes males to increased adiposity and metabolic dysregulation. In apparent contrast, however, obesity in men has been associated with hyperestrogenemia, and, further, excessive estradiol exposure has been postulated to play an exacerbating role in the progression of obesity and attendant metabolic dysregulation. Though not uniformly, obesity in men is often characterized by a profile of low circulating androgens but elevated levels of circulating estrone and 17 $\beta$ -estradiol (Schneider et al. 1979; MacDonald et al. 2010). The reasons for this variable co-occurrence of obesity and hyperestrogenemia in men are not well defined but may include repeat number of a TTTA polymorphism in the aromatase gene *CYP19A1* (Hammoud et al. 2010). Although overtly elevated serum estrogen levels are not found in all men with obesity, it has been proposed that obesity also may represent a state of relative rather than absolute estrogen excess. Thus, increased peripheral aromatization of testosterone in obese men may lead to enhanced central estradiol signaling that suppresses gonadotropin production and contributes to a sustained state of hypogonadotropic hypogonadism (Mah and Wittert 2010). This serum profile of sex steroids is normalized with weight loss, as serum testosterone and gonadotropin levels rise, whereas serum estradiol levels fall subsequent to weight loss effected either through bariatric surgery or behavioral change (Armamento-Villareal et al. 2016; Corona et al. 2013; Mihalca and Fica 2014;



Pellitero et al. 2012). Thus, whether absolute or relative, estrogen excess is believed to have a bidirectional relationship with obesity in men and to contribute to progressive adiposity and metabolic dysregulation (Corona et al. 2011; Mah and Wittert 2010).

Indeed, some preclinical evidence supports pro-adipogenic effects of estradiol. In male but not female preadipocytes,  $17\beta$ -estradiol induced aromatase activity, leading the authors to postulate that excess estradiol within adipose tissue may be self-propagating and contribute to progressive increases in leptin and cortisol signaling with attendant pro-adipogenic effects (Dieudonné et al. 2006). Further, enhanced conversion of testosterone to estradiol could cause a relative androgen depletion and thereby limit the anti-adipogenic effects conferred by androgens within adipose tissue (Dieudonné et al. 2000). One possible way to reconcile the apparent paradox of intra-adipose estradiol as both pro- and anti-adipogenic is to view obesity as a dynamic rather than static state, one characterized by positive energy balance and continual delivery of excess glucose and lipids to peripheral tissue. Adipose tissue remains the primary sink for this excess energy intake, but fat mass expansion in obesity becomes increasingly limited by adequacy of blood and oxygen supply as well as physical constraints. Viewed in this context, increased estradiol generation within adipose tissue could be seen as an adaptation with variable effects on adipogenesis and lipid storage that serve to both restrain adipogenesis and maintain some capacity to store the excess glucose and lipid that otherwise would contribute to ectopic fat accrual.

Importantly, even as this increased estradiol production may be adaptive, it may nevertheless confer both harmful and beneficial effects with regard to metabolic regulation. In this model, estradiol is a regulatory mediator that can exert either pro- or anti-adipogenic effects or both concurrently. With regard to adipogenesis, for example,  $17\beta$ -estradiol was shown to inhibit  $11\beta$ -HSD1 activity in adipocytes from male rats, thus suppressing the formation of pro-adipogenic cortisol (Tagawa et al. 2009). However, it also increases leptin expression and secretion, which, in turn, enhances  $11\beta$ -HSD1 expression in preadipocytes and, moreover, promotes further estradiol generation through upregulation of aromatase (Dieudonné et al. 2006). The concentration-dependent effects of estradiol on Lpl activity further demonstrate the potential for estradiol to play divergent roles in lipid uptake by adipocytes, again indicating estradiol could either inhibit or promote lipid accumulation in adipocytes. Consequently, the net impact on adipogenesis and fat mass will be contingent on local estradiol concentrations and concurrent signals in the tissue environment as well as the total delivery of energy substrate to adipose tissue (Fig. 3). These context-dependent effects of estradiol are also illustrated by estradiol-mediated regulation of  $\text{TNF}\alpha$ . At higher concentrations,  $\text{TNF}\alpha$  can inhibit adipocyte differentiation, promote lipolysis, and inhibit insulin-stimulated glucose uptake, thus acting as a potent anti-adipogenic signal (Ruan et al. 2002). Therefore, estradiol-mediated suppression of  $\text{TNF}\alpha$  production would serve to promote adipogenesis, lipid storage, and glucose uptake in adipocytes. However, these anti-adipogenic effects of  $\text{TNF}\alpha$  are concentration dependent, as are the inhibitory effects of estradiol on  $\text{TNF}\alpha$  generation. Thus, pro-adipogenic effects of estradiol through  $\text{TNF}\alpha$  suppres-



**Fig. 3** Estradiol mediates myriad effects within adipose tissue and contributes to the regulation of adipocyte differentiation, nutrient uptake, and lipolysis. When viewed in isolation, these effects could be seen as either pro- or anti-obesogenic. The cumulative effect of estradiol on fat mass accrual is contingent upon context and, critically, overall energy balance

sion only would be evident in obesity or other states characterized by elevated production of both estradiol and TNF $\alpha$  within adipose tissue. Conversely, in a state of neutral or negative energy balance, TNF $\alpha$  production is generally lower, which may be one factor that allows the anti-adipogenic effects of estradiol to become manifest.

Estradiol excess therefore may not truly represent an aberrant response that promotes further fat mass accrual in the setting of obesity; rather, a more physiologically relevant model may be one of a propagated, amplified process consequent to a continued state of positive energy balance. Thus, the process may be wholly regulated and reversible, as supported by the normalization of serum estradiol levels as well as marked improvements in metabolic regulation in obese subjects after induction of negative energy balance leading to body weight reductions (Petersen et al. 2005; Viljanen et al. 2009; Wing and Group 2010). This model suggests that increased estradiol production within adipose tissue is an adaptive response to continual delivery of nutrient excess rather than a primary pathogenic driver of obesity in men. The increased estradiol production may be promoting continued – though not unrestrained – adipogenesis as well as nutrient uptake in order to handle excess lipid and glucose, thus maintaining adipose tissue as the primary reservoir for energy storage while addressing the constraints on adipose tissue expansion. An adaptive rather than pathogenic role of increased intra-adipose estradiol is further supported by clinical studies of aromatase inhibitors in obese men. Although aromatase inhibition reduces circulating estradiol levels and restores normal circulating testosterone levels, clinical intervention trials to date have failed to show any associated metabolic benefit (Burnett-Bowie et al. 2009; Loves et al. 2008, 2013).

These negative findings underscore the importance of understanding estradiol as a paracrine and intracrine mediator rather than solely assessing circulating levels (Simpson 2003).

## Clinical Intervention Studies

Only over the past few years have clinical intervention studies begun to confirm preclinical evidence that estradiol contributes to body weight regulation and metabolic health in men. One small study examined the effects of testosterone replacement in obese men with low-normal baseline serum testosterone concentrations. Whereas treatment with testosterone gel led to significant reductions in adiposity, these changes were not seen when testosterone was co-administered with an aromatase inhibitor (Juang et al. 2014). In a larger study of healthy men, two subject cohorts were administered the GnRH analogue goserelin acetate to suppress endogenous sex steroid production. Simultaneously, subjects in the first cohort received either placebo gel or variable doses of add-back testosterone gel, and the second cohort of subjects received either placebo gel or testosterone gel with an aromatase inhibitor. Strikingly, whereas androgen exposure appeared to mediate changes in lean mass, estradiol rather than testosterone was found to be the primary determinant of changes in fat mass (Finkelstein et al. 2013). Subsequently, another clinical study similarly enrolled healthy, eugonadal men and rendered them medically castrate through use of the GnRH antagonist acyline. Subjects in this study variably received placebo gel, low-dose or full replacement dose testosterone gel, or full replacement dose testosterone gel with an aromatase inhibitor. In all three treatment groups rendered sex steroid deficient, significant increases in body fat mass were evident within only 4 weeks of drug treatment (Chao et al. 2016). Again, estradiol rather than testosterone deprivation exhibited a stronger correlation with the observed increases in adiposity.

## Implications for Clinical Practice

Better understanding of the importance of estrogens for maintaining metabolic health in men is essential for optimal treatment of male hypogonadism and, further, for understanding the metabolic implications of sex steroid manipulation in clinical practice. Exogenous testosterone therapy in hypogonadal men restores circulating androgen levels but not fertility, prompting interest in identifying alternative therapeutic strategies. The ER antagonist clomiphene and its derivatives also have been proposed as therapeutic interventions for secondary hypogonadism in men (Wiehle et al. 2013). Clomiphene blocks estradiol-mediated gonadotropin suppression and

thereby helps restore normal testosterone production while preserving fertility (Kaminetsky et al. 2013; Kim et al. 2016; Wiehle et al. 2014). The use of aromatase inhibitors also has been proposed for men with hypogonadism associated with hyperestrogenemia, including subsets of men with late-onset and obesity-associated hypogonadotropic hypogonadism (de Boer et al. 2005; Tan et al. 2014; Zumoff et al. 2003). However, as appreciation grows of the critical metabolic roles of estrogens in men, caution may be warranted in the pursuit of such anti-estrogen-based approaches to treatment of male hypogonadism. Similarly, use of selective androgen receptor modulators for treatment of hypogonadism has been proposed (Bhattacharya et al. 2016; Thirumalai et al. 2017), but this strategy may not fully restore estradiol signaling and, therefore, fail to optimize metabolic health in hypogonadal men. Rather, selective estrogen receptor modulators may prove equally critical for improving body composition and metabolic regulation in male hypogonadism. Novel, targeted pharmacological strategies that promote ER $\alpha$  signaling may prove important not only for treatment of male hypogonadism, as a dual ER $\alpha$ /GLP-1 agonist has been developed as a potential therapeutic for metabolic disorders (Finan et al. 2012).

Another population for whom the metabolic effects of estradiol could prove highly relevant are men with prostate cancer. In the USA, prostate cancer affects 2 million men, and up to 50% of these men will undergo androgen deprivation therapy (ADT) at some point in their treatment course (Meng et al. 2002). The most common form of ADT involves GnRH analogues that confer central hypogonadism, and over the past decade, clinical evidence has compellingly demonstrated the men undergoing ADT are at substantially higher risk of increased adiposity, insulin resistance, T2DM, and cardiovascular disease than age-matched controls with or without prostate cancer (Cannata et al. 2012; Hamilton et al. 2011; Keating et al. 2006, 2012; Shahani et al. 2008). ADT-induced hypogonadism is a state of both androgen and estrogen deficiency, and the latter is now believed to contribute substantially to the metabolic dysregulation evident in men receiving GnRH analogues. Interestingly, estradiol therapy was among the ADT formulations originally used for treatment of prostate cancer (Cannata et al. 2012), and interest in estrogen-based ADT recently has been renewed as it could effectively suppress androgen production while reducing the metabolic sequelae of GnRH analogues (Phillips et al. 2014).

Finally, as efforts continue to develop an effective form of hormonal contraception for men (Ayoub et al. 2016; Zitzmann et al. 2017), these findings collectively underscore the need to carefully assess changes in estradiol exposure consequent to different contraceptive regimens. Thus, mounting evidence suggests that estradiol replacement is a pivotal facet of the treatment of male hypogonadism and, by corollary, states of estradiol deprivation – whether consequent to physiologic hypogonadism, androgen deprivation therapy, or hormonal forms of contraception – must be avoided as possible to optimize metabolic health in men.

## References

- Abdelgadir, S. E., Resko, J. A., Ojeda, S. R., Lephart, E. D., McPhaul, M. J., & Roselli, C. E. (1994). Androgens regulate aromatase cytochrome P450 messenger ribonucleic acid in rat brain. *Endocrinology*, *135*, 395–401.
- Ahima, R. S., Stanley, T. L., Khor, V. K., Zanni, M. V., & Grinspoon, S. K. (2011). Estrogen sulfotransferase is expressed in subcutaneous adipose tissue of obese humans in association with TNF-alpha and SOCS3. *The Journal of Clinical Endocrinology and Metabolism*, *96*, E1153–E1158.
- Anderson, L. A., McTernan, P. G., Barnett, A. H., & Kumar, S. (2001). The effects of androgens and estrogens on preadipocyte proliferation in human adipose tissue: Influence of gender and site. *The Journal of Clinical Endocrinology and Metabolism*, *86*, 5045–5051.
- Archer, Z. A., Findlay, P. A., McMillen, S. R., Rhind, S. M., & Adam, C. L. (2004). Effects of nutritional status and gonadal steroids on expression of appetite-regulatory genes in the hypothalamic arcuate nucleus of sheep. *The Journal of Endocrinology*, *182*, 409–419.
- Armamento-Villareal, R., Aguirre, L. E., Qualls, C., & Villareal, D. T. (2016). Effect of lifestyle intervention on the hormonal profile of frail, obese older men. *The Journal of Nutrition, Health & Aging*, *20*, 334–340.
- Ayoub, R., Page, S. T., Swerdloff, R. S., Liu, P. Y., Amory, J. K., Leung, A., Hull, L., Blithe, D., Christy, A., Chao, J. H., Bremner, W. J., & Wang, C. (2016). Comparison of the single dose pharmacokinetics, pharmacodynamics, and safety of two novel oral formulations of dimethandrolone undecanoate (DMAU): A potential oral, male contraceptive. *Andrology*, *5*(2), 278–285.
- Barros, R. P., Machado, U. F., Warner, M., & Gustafsson, J. A. (2006). Muscle GLUT4 regulation by estrogen receptors ERbeta and ERalpha. *Proceedings of the National Academy of Sciences of the United States of America*, *103*, 1605–1608.
- Barros, R. P., Gabbi, C., Morani, A., Warner, M., & Gustafsson, J. A. (2009). Participation of ERalpha and ERbeta in glucose homeostasis in skeletal muscle and white adipose tissue. *American Journal of Physiology Endocrinology and Metabolism*, *297*, E124–E133.
- Bélanger, C., Hould, F. S., Lebel, S., Biron, S., Brochu, G., & Tchernof, A. (2006). Omental and subcutaneous adipose tissue steroid levels in obese men. *Steroids*, *71*, 674–682.
- Bhasin, S., Woodhouse, L., & Storer, T. W. (2003). Androgen effects on body composition. *Growth Hormone & IGF Research*, *13*(Suppl A), S63–S71.
- Bhasin, S., Cunningham, G. R., Hayes, F. J., Matsumoto, A. M., Snyder, P. J., Swerdloff, R. S., Montori, V. M., & Task Force, E. S. (2010). Testosterone therapy in men with androgen deficiency syndromes: An endocrine society clinical practice guideline. *The Journal of Clinical Endocrinology and Metabolism*, *95*, 2536–2559.
- Bhattacharya, I., Tarabar, S., Liang, Y., Pradhan, V., Owens, J., & Oemar, B. (2016). Safety, pharmacokinetic, and pharmacodynamic evaluation after single and multiple ascending doses of a novel selective androgen receptor modulator in healthy subjects. *Clinical Therapeutics*, *38*, 1401–1416.
- Blankenstein, M. A., Szymczak, J., Daroszewski, J., Milewicz, A., & Thijssen, J. H. (1992). Estrogens in plasma and fatty tissue from breast cancer patients and women undergoing surgery for non-oncological reasons. *Gynecological Endocrinology*, *6*, 13–17.
- Blasko, E., Haskell, C. A., Leung, S., Gualtieri, G., Halks-Miller, M., Mahmoudi, M., Dennis, M. K., Prossnitz, E. R., Karpus, W. J., & Horuk, R. (2009). Beneficial role of the GPR30 agonist G-1 in an animal model of multiple sclerosis. *Journal of Neuroimmunology*, *214*, 67–77.
- Brind, J., Strain, G., Miller, L., Zumoff, B., Vogelmann, J., & Orentreich, N. (1990). Obese men have elevated plasma levels of estrone sulfate. *International Journal of Obesity*, *14*, 483–486.
- Brown, L. M., & Clegg, D. J. (2010). Central effects of estradiol in the regulation of food intake, body weight, and adiposity. *The Journal of Steroid Biochemistry and Molecular Biology*, *122*, 65–73.

- Brown, T. J., Naftolin, F., & Maclusky, N. J. (1992). Sex differences in estrogen receptor binding in the rat hypothalamus: Effects of subsaturating pulses of estradiol. *Brain Research*, 578, 129–134.
- Burnett-Bowie, S. A., Ruppenian, K. C., Dere, M. E., Lee, H., & Leder, B. Z. (2009). Effects of aromatase inhibition in hypogonadal older men: A randomized, double-blind, placebo-controlled trial. *Clinical Endocrinology (Oxf)*, 70, 116–123.
- Cannata, D. H., Kirschenbaum, A., & Levine, A. C. (2012). Androgen deprivation therapy as primary treatment for prostate cancer. *The Journal of Clinical Endocrinology and Metabolism*, 97, 360–365.
- Carani, C., Qin, K., Simoni, M., Faustini-Fustini, M., Serpente, S., Boyd, J., Korach, K. S., & Simpson, E. R. (1997). Effect of testosterone and estradiol in a man with aromatase deficiency. *The New England Journal of Medicine*, 337, 91–95.
- Carrier, N., Saland, S. K., Duclot, F., He, H., Mercer, R., & Kabbaj, M. (2015). The anxiolytic and antidepressant-like effects of testosterone and estrogen in gonadectomized male rats. *Biological Psychiatry*, 78, 259–269.
- Castanho, T. C., Moreira, P. S., Portugal-Nunes, C., Novais, A., Costa, P. S., Palha, J. A., Sousa, N., & Santos, N. C. (2014). The role of sex and sex-related hormones in cognition, mood and well-being in older men and women. *Biological Psychology*, 103, 158–166.
- Cederroth, C. R., Vinciguerra, M., Kühne, F., Madani, R., Doerge, D. R., Visser, T. J., Foti, M., Rohner-Jeanrenaud, F., Vassalli, J. D., & Nef, S. (2007). A phytoestrogen-rich diet increases energy expenditure and decreases adiposity in mice. *Environmental Health Perspectives*, 115, 1467–1473.
- Cederroth, C. R., Vinciguerra, M., Gjinovci, A., Kühne, F., Klein, M., Cederroth, M., Caille, D., Suter, M., Neumann, D., James, R. W., Doerge, D. R., Wallimann, T., Meda, P., Foti, M., Rohner-Jeanrenaud, F., Vassalli, J. D., & Nef, S. (2008). Dietary phytoestrogens activate AMP-activated protein kinase with improvement in lipid and glucose metabolism. *Diabetes*, 57, 1176–1185.
- Chakraborty, S., Sachdev, A., Salton, S. R., & Chakraborty, T. R. (2008). Stereological analysis of estrogen receptor expression in the hypothalamic arcuate nucleus of ob/ob and agouti mice. *Brain Research*, 1217, 86–95.
- Chao, J., Rubinow, K. B., Kratz, M., Amory, J. K., Matsumoto, A. M., & Page, S. T. (2016). Short-term estrogen withdrawal increases adiposity in healthy men. *The Journal of Clinical Endocrinology and Metabolism*, 101, 3724–3731.
- Clegg, D. J., Brown, L. M., Woods, S. C., & Benoit, S. C. (2006). Gonadal hormones determine sensitivity to central leptin and insulin. *Diabetes*, 55, 978–987.
- Clegg, D. J., Brown, L. M., Zigman, J. M., Kemp, C. J., Strader, A. D., Benoit, S. C., Woods, S. C., Mangiaracina, M., & Geary, N. (2007). Estradiol-dependent decrease in the orexigenic potency of ghrelin in female rats. *Diabetes*, 56, 1051–1058.
- Cooke, P. S., Heine, P. A., Taylor, J. A., & Lubahn, D. B. (2001). The role of estrogen and estrogen receptor- $\alpha$  in male adipose tissue. *Molecular and Cellular Endocrinology*, 178, 147–154.
- Corona, G., Rastrelli, G., Morelli, A., Vignozzi, L., Mannucci, E., & Maggi, M. (2011). Hypogonadism and metabolic syndrome. *Journal of Endocrinological Investigation*, 34, 557–567.
- Corona, G., Rastrelli, G., Monami, M., Saad, F., Luconi, M., Lucchese, M., Facchiano, E., Sforza, A., Forti, G., Mannucci, E., & Maggi, M. (2013). Body weight loss reverts obesity-associated hypogonadotropic hypogonadism: A systematic review and meta-analysis. *European Journal of Endocrinology*, 168, 829–843.
- Cunningham, M., & Gilkeson, G. (2011). Estrogen receptors in immunity and autoimmunity. *Clinical Reviews in Allergy & Immunology*, 40, 66–73.
- D'Eon, T. M., Souza, S. C., Aronovitz, M., Obin, M. S., Fried, S. K., & Greenberg, A. S. (2005). Estrogen regulation of adiposity and fuel partitioning. Evidence of genomic and non-genomic regulation of lipogenic and oxidative pathways. *The Journal of Biological Chemistry*, 280, 35983–35991.



- Dakin, R. S., Walker, B. R., Seckl, J. R., Hadoke, P. W., & Drake, A. J. (2015). Estrogens protect male mice from obesity complications and influence glucocorticoid metabolism. *International Journal of Obesity (Lond)*, 39, 1539–1547.
- Davis, K. E., Carstens, E. J., Irani, B. G., Gent, L. M., Hahner, L. M., & Clegg, D. J. (2014). Sexually dimorphic role of G protein-coupled estrogen receptor (GPER) in modulating energy homeostasis. *Hormones and Behavior*, 66(1), 196–207.
- de Boer, H., Verschoor, L., Ruinemans-Koerts, J., & Jansen, M. (2005). Letrozole normalizes serum testosterone in severely obese men with hypogonadotropic hypogonadism. *Diabetes, Obesity & Metabolism*, 7, 211–215.
- Deslypere, J. P., Verdonck, L., & Vermeulen, A. (1985). Fat tissue: A steroid reservoir and site of steroid metabolism. *The Journal of Clinical Endocrinology and Metabolism*, 61, 564–570.
- Dieudonne, M. N., Pecquery, R., Leneuve, M. C., & Giudicelli, Y. (2000). Opposite effects of androgens and estrogens on adipogenesis in rat preadipocytes: Evidence for sex and site-related specificities and possible involvement of insulin-like growth factor 1 receptor and peroxisome proliferator-activated receptor gamma2. *Endocrinology*, 141, 649–656.
- Dieudonné, M. N., Leneuve, M. C., Giudicelli, Y., & Pecquery, R. (2004). Evidence for functional estrogen receptors alpha and beta in human adipose cells: Regional specificities and regulation by estrogens. *American Journal of Physiology Cell Physiology*, 286, C655–C661.
- Dieudonné, M. N., Sammari, A., Dos Santos, E., Leneuve, M. C., Giudicelli, Y., & Pecquery, R. (2006). Sex steroids and leptin regulate 11beta-hydroxysteroid dehydrogenase I and P450 aromatase expressions in human preadipocytes: Sex specificities. *The Journal of Steroid Biochemistry and Molecular Biology*, 99, 189–196.
- Ding, E. L., Song, Y., Malik, V. S., & Liu, S. (2006). Sex differences of endogenous sex hormones and risk of type 2 diabetes: A systematic review and meta-analysis. *JAMA*, 295, 1288–1299.
- Fan, W., Yanase, T., Nomura, M., Okabe, T., Goto, K., Sato, T., Kawano, H., Kato, S., & Nawata, H. (2005). Androgen receptor null male mice develop late-onset obesity caused by decreased energy expenditure and lipolytic activity but show normal insulin sensitivity with high adiponectin secretion. *Diabetes*, 54, 1000–1008.
- Finan, B., Yang, B., Ottaway, N., Stemmer, K., Müller, T. D., Yi, C. X., Habegger, K., et al. (2012). Targeted estrogen delivery reverses the metabolic syndrome. *Nature Medicine*, 18, 1847–1856.
- Finkelstein, J. S., Lee, H., Burnett-Bowie, S. A., Pallais, J. C., Yu, E. W., Borges, L. F., Jones, B. F., Barry, C. V., Wulczyn, K. E., Thomas, B. J., & Leder, B. Z. (2013). Gonadal steroids and body composition, strength, and sexual function in men. *The New England Journal of Medicine*, 369, 1011–1022.
- Flores, R., Shi, J., Fuhrman, B., Xu, X., Veenstra, T. D., Gail, M. H., Gajer, P., Ravel, J., & Goedert, J. J. (2012). Fecal microbial determinants of fecal and systemic estrogens and estrogen metabolites: A cross-sectional study. *Journal of Translational Medicine*, 10, 253.
- Foryst-Ludwig, A., & Kintscher, U. (2010). Metabolic impact of estrogen signalling through ERalpha and ERbeta. *The Journal of Steroid Biochemistry and Molecular Biology*, 122, 74–81.
- Foryst-Ludwig, A., Clemenz, M., Hohmann, S., Hartge, M., Sprang, C., Frost, N., Krikov, M., Bhanot, S., Barros, R., Morani, A., Gustafsson, J. A., Unger, T., & Kintscher, U. (2008). Metabolic actions of estrogen receptor beta (ERbeta) are mediated by a negative cross-talk with PPARgamma. *PLoS Genetics*, 4, e1000108.
- Frank, A., Brown, L. M., & Clegg, D. J. (2014). The role of hypothalamic estrogen receptors in metabolic regulation. *Frontiers in Neuroendocrinology*, 35, 550–557.
- Gao, Q., Mezei, G., Nie, Y., Rao, Y., Choi, C. S., Bechmann, I., Leranth, C., Toran-Allerand, D., Priest, C. A., Roberts, J. L., Gao, X. B., Mobbs, C., Shulman, G. I., Diano, S., & Horvath, T. L. (2007). Anorectic estrogen mimics leptin's effect on the rewiring of melanocortin cells and Stat3 signaling in obese animals. *Nature Medicine*, 13, 89–94.
- Gerriets, V. A., & MacIver, N. J. (2014). Role of T cells in malnutrition and obesity. *Frontiers in Immunology*, 5, 379.



- Gillies, G. E., & McArthur, S. (2010). Estrogen actions in the brain and the basis for differential action in men and women: A case for sex-specific medicines. *Pharmacological Reviews*, 62, 155–198.
- Giudicelli, Y., Dieudonne, M. N., Lacasa, D., Pasquier, Y. N., & Pecquery, R. (1993). Modulation by sex hormones of the membranous transducing system regulating fatty acid mobilization in adipose tissue. *Prostaglandins, Leukotrienes, and Essential Fatty Acids*, 48, 91–100.
- Grasa, M. M., Esteve, M., Masanés, R. M., Yubero, P., Blay, M., López-Martí, J., Cabot, C., Vilà, R., Fernández-López, J. A., Remesar, X., & Alemany, M. (2001). Oral gavage of oleoyl-oestrone has a stronger effect on body weight in male Zucker obese rats than in female. *Diabetes, Obesity & Metabolism*, 3, 203–208.
- Hamilton, E. J., Gianatti, E., Strauss, B. J., Wentworth, J., Lim-Joon, D., Bolton, D., Zajac, J. D., & Grossmann, M. (2011). Increase in visceral and subcutaneous abdominal fat in men with prostate cancer treated with androgen deprivation therapy. *Clinical Endocrinology*, 74, 377–383.
- Hammoud, A., Carrell, D. T., Meikle, A. W., Xin, Y., Hunt, S. C., Adams, T. D., & Gibson, M. (2010). An aromatase polymorphism modulates the relationship between weight and estradiol levels in obese men. *Fertility and Sterility*, 94, 1734–1738.
- Harada, N., Hanaoka, R., Horiuchi, H., Kitakaze, T., Mitani, T., Inui, H., & Yamaji, R. (2016). Castration influences intestinal microflora and induces abdominal obesity in high-fat diet-fed mice. *Scientific Reports*, 6, 23001.
- Heine, P. A., Taylor, J. A., Iwamoto, G. A., Lubahn, D. B., & Cooke, P. S. (2000). Increased adipose tissue in male and female estrogen receptor-alpha knockout mice. *Proceedings of the National Academy of Sciences of the United States of America*, 97, 12729–12734.
- Hemsell, D. L., Grodin, J. M., Brenner, P. F., Siiteri, P. K., & MacDonald, P. C. (1974). Plasma precursors of estrogen. II. Correlation of the extent of conversion of plasma androstenedione to estrone with age. *The Journal of Clinical Endocrinology and Metabolism*, 38, 476–479.
- Holland, A. M., Roberts, M. D., Mumford, P. W., Mobley, C. B., Kephart, W. C., Conover, C. F., Beggs, L. A., Balaz, A., Otzel, D. M., Yarrow, J. F., Borst, S. E., & Beck, D. T. (2016). Testosterone inhibits expression of lipogenic genes in visceral fat by an estrogen-dependent mechanism. *Journal of Applied Physiology*. (1985, 121, 792–805.
- Homma, H., Kurachi, H., Nishio, Y., Takeda, T., Yamamoto, T., Adachi, K., Morishige, K., Ohmichi, M., Matsuzawa, Y., & Murata, Y. (2000). Estrogen suppresses transcription of lipoprotein lipase gene. Existence of a unique estrogen response element on the lipoprotein lipase promoter. *The Journal of Biological Chemistry*, 275, 11404–11411.
- Ihunnah, C. A., Wada, T., Philips, B. J., Ravuri, S. K., Gibbs, R. B., Kirisci, L., Rubin, J. P., Marra, K. G., & Xie, W. (2014). Estrogen Sulfotransferase/SULT1E1 promotes human adipogenesis. *Molecular and Cellular Biology*, 34, 1682–1694.
- Isidori, A. M., Giannetta, E., Greco, E. A., Gianfrilli, D., Bonifacio, V., Isidori, A., Lenzi, A., & Fabbri, A. (2005). Effects of testosterone on body composition, bone metabolism and serum lipid profile in middle-aged men: A meta-analysis. *Clinical Endocrinology (Oxf)*, 63, 280–293.
- Jasuja, G. K., Travison, T. G., Davda, M., Murabito, J. M., Basaria, S., Zhang, A., Kushnir, M. M., Rockwood, A. L., Meikle, W., Pencina, M. J., Coviello, A., Rose, A. J., D'Agostino, R., Vasan, R. S., & Bhasin, S. (2013a). Age trends in estradiol and estrone levels measured using liquid chromatography tandem mass spectrometry in community-dwelling men of the Framingham heart study. *The Journals of Gerontology Series A, Biological Sciences and Medical Sciences*, 68, 733–740.
- Jasuja, G. K., Travison, T. G., Davda, M., Rose, A. J., Zhang, A., Kushnir, M. M., Rockwood, A. L., Meikle, W., Coviello, A. D., D'Agostino, R., Vasan, R. S., & Bhasin, S. (2013b). Circulating estrone levels are associated prospectively with diabetes risk in men of the Framingham Heart Study. *Diabetes Care*, 36, 2591–2596.
- Jones, M. E., Thorburn, A. W., Britt, K. L., Hewitt, K. N., Wreford, N. G., Proietto, J., Oz, O. K., Leury, B. J., Robertson, K. M., Yao, S., & Simpson, E. R. (2000). Aromatase-deficient (ArKO) mice have a phenotype of increased adiposity. *Proceedings of the National Academy of Sciences of the United States of America*, 97, 12735–12740.

- Jones, M. E., Thorburn, A. W., Britt, K. L., Hewitt, K. N., Misso, M. L., Wreford, N. G., Proietto, J., Oz, O. K., Leury, B. J., Robertson, K. M., Yao, S., & Simpson, E. R. (2001). Aromatase-deficient (ArKO) mice accumulate excess adipose tissue. *The Journal of Steroid Biochemistry and Molecular Biology*, 79, 3–9.
- Jones, M. E., Boon, W. C., Proietto, J., & Simpson, E. R. (2006). Of mice and men: The evolving phenotype of aromatase deficiency. *Trends in Endocrinology and Metabolism*, 17, 55–64.
- Jones, T. H., Arver, S., Behre, H. M., Buvat, J., Meuleman, E., Moncada, I., Morales, A. M., Volterrani, M., Yellowlees, A., Howell, J. D., Channer, K. S., & Investigators, T. (2011). Testosterone replacement in hypogonadal men with type 2 diabetes and/or metabolic syndrome (the TIMES2 study). *Diabetes Care*, 34, 828–837.
- Juang, P. S., Peng, S., Allehmazadeh, K., Shah, A., Coviello, A. D., & Herbst, K. L. (2014). Testosterone with dutasteride, but not anastrozole, improves insulin sensitivity in young obese men: A randomized controlled trial. *The Journal of Sexual Medicine*, 11, 563–573.
- Kahles, F., Meyer, C., Möllmann, J., Diebold, S., Findeisen, H. M., Lebherz, C., Trautwein, C., Koch, A., Tacke, F., Marx, N., & Lehrke, M. (2014). GLP-1 secretion is increased by inflammatory stimuli in an IL-6-dependent manner, leading to hyperinsulinemia and blood glucose lowering. *Diabetes*, 63, 3221–3229.
- Kaminetsky, J., Werner, M., Fontenot, G., & Wiehle, R. D. (2013). Oral enclomiphene citrate stimulates the endogenous production of testosterone and sperm counts in men with low testosterone: comparison with testosterone gel. *The Journal of Sexual Medicine*, 10, 1628–1635.
- Kautzky-Willer, A., & Handisurya, A. (2009). Metabolic diseases and associated complications: Sex and gender matter! *European Journal of Clinical Investigation*, 39, 631–648.
- Keating, N. L., O'Malley, A. J., & Smith, M. R. (2006). Diabetes and cardiovascular disease during androgen deprivation therapy for prostate cancer. *Journal of Clinical Oncology*, 24, 4448–4456.
- Keating, N. L., O'Malley, A., Freedland, S. J., & Smith, M. R. (2012). Diabetes and cardiovascular disease during androgen deprivation therapy: Observational study of veterans with prostate cancer. *Journal of the National Cancer Institute*, 104, 1518–1523.
- Kellert, B. A., Nguyen, M. C., Nguyen, C., Nguyen, Q. H., & Wagner, E. J. (2009). Estrogen rapidly attenuates cannabinoid-induced changes in energy homeostasis. *European Journal of Pharmacology*, 622, 15–24.
- Khan, M. J., Gerasimidis, K., Edwards, C. A., & Shaikh, M. G. (2016). Role of gut microbiota in the aetiology of obesity: Proposed mechanisms and review of the literature. *Journal of Obesity*, 2016, 7353642.
- Khor, V. K., Tong, M. H., Qian, Y., & Song, W. C. (2008). Gender-specific expression and mechanism of regulation of estrogen sulfotransferase in adipose tissues of the mouse. *Endocrinology*, 149, 5440–5448.
- Kim, E. D., McCullough, A., & Kaminetsky, J. (2016). Oral enclomiphene citrate raises testosterone and preserves sperm counts in obese hypogonadal men, unlike topical testosterone: Restoration instead of replacement. *BJU International*, 117, 677–685.
- Kley, H. K., Deselaers, T., Peerenboom, H., & Kruskemper, H. L. (1980a). Enhanced conversion of androstenedione to estrogens in obese males. *The Journal of Clinical Endocrinology and Metabolism*, 51, 1128–1132.
- Kley, H. K., Edelmann, P., & Kruskemper, H. L. (1980b). Relationship of plasma sex hormones to different parameters of obesity in male subjects. *Metabolism*, 29, 1041–1045.
- Kovats, S. (2012). Estrogen receptors regulate an inflammatory pathway of dendritic cell differentiation: Mechanisms and implications for immunity. *Hormones and Behavior*, 62, 254–262.
- Kovats, S. (2015). Estrogen receptors regulate innate immune cells and signaling pathways. *Cellular Immunology*, 294, 63–69.
- Lacasa, D., Taleb, S., Keophipath, M., Miranville, A., & Clement, K. (2007). Macrophage-secreted factors impair human adipogenesis: Involvement of proinflammatory state in preadipocytes. *Endocrinology*, 148, 868–877.
- Lebherz, C., Kahles, F., Piotrowski, K., Vogeser, M., Foldenauer, A. C., Nassau, K., Kilger, E., Marx, N., Parhofer, K. G., & Lehrke, M. (2016). Interleukin-6 predicts inflammation-induced

- increase of Glucagon-like peptide-1 in humans in response to cardiac surgery with association to parameters of glucose metabolism. *Cardiovascular Diabetology*, 15, 21.
- Loves, S., Ruinmans-Koerts, J., & de Boer, H. (2008). Letrozole once a week normalizes serum testosterone in obesity-related male hypogonadism. *European Journal of Endocrinology*, 158, 741–747.
- Loves, S., de Jong, J., van Sorge, A., Telting, D., Tack, C. J., Hermus, A., Westerterp, K., & de Boer, H. (2013). Somatic and psychological effects of low-dose aromatase inhibition in men with obesity-related hypogonadotropic hypotestosteronemia. *European Journal of Endocrinology*, 169, 705–714.
- Lu, C., Kumar, P. A., Fan, Y., Sperling, M. A., & Menon, R. K. (2010). A novel effect of growth hormone on macrophage modulates macrophage-dependent adipocyte differentiation. *Endocrinology*, 151, 2189–2199.
- Lumeng, C. N., DelProposto, J. B., Westcott, D. J., & Saltiel, A. R. (2008). Phenotypic switching of adipose tissue macrophages with obesity is generated by spatiotemporal differences in macrophage subtypes. *Diabetes*, 57, 3239–3246.
- MacDonald, A. A., Herbison, G. P., Showell, M., & Farquhar, C. M. (2010). The impact of body mass index on semen parameters and reproductive hormones in human males: A systematic review with meta-analysis. *Human Reproduction Update*, 16, 293–311.
- Maffei, L., Rochira, V., Zirilli, L., Antunez, P., Aranda, C., Fabre, B., Simone, M. L., Pignatti, E., Simpson, E. R., Houssami, S., Clyne, C. D., & Carani, C. (2007). A novel compound heterozygous mutation of the aromatase gene in an adult man: Reinforced evidence on the relationship between congenital oestrogen deficiency, adiposity and the metabolic syndrome. *Clinical Endocrinology*, 67, 218–224.
- Mah, P. M., & Wittert, G. A. (2010). Obesity and testicular function. *Molecular and Cellular Endocrinology*, 316, 180–186.
- Mather, K. J., Kim, C., Christophi, C. A., Aroda, V. R., Knowler, W. C., Edelstein, S. E., Florez, J. C., Labrie, F., Kahn, S. E., Goldberg, R. B., Barrett-Connor, E., & Program, D. P. (2015). Steroid sex hormones, sex hormone-binding globulin, and diabetes incidence in the diabetes prevention program. *The Journal of Clinical Endocrinology and Metabolism*, 100, 3778–3786.
- Mathis, D. (2013). Immunological goings-on in visceral adipose tissue. *Cell Metabolism*, 17, 851–859.
- Matsumine, H., Hirato, K., Yanaihara, T., Tamada, T., & Yoshida, M. (1986). Aromatization by skeletal muscle. *The Journal of Clinical Endocrinology and Metabolism*, 63, 717–720.
- Mauvais-Jarvis, F., Clegg, D. J., & Hevener, A. L. (2013). The role of estrogens in control of energy balance and glucose homeostasis. *Endocrine Reviews*, 34, 309–338.
- Meng, M. V., Grossfeld, G. D., Sadetsky, N., Mehta, S. S., Lubeck, D. P., & Carroll, P. R. (2002). Contemporary patterns of androgen deprivation therapy use for newly diagnosed prostate cancer. *Urology*, 60, 7–11. discussion 11–12.
- Merchenthaler, I., Lane, M. V., Numan, S., & Dellovade, T. L. (2004). Distribution of estrogen receptor alpha and beta in the mouse central nervous system: In vivo autoradiographic and immunocytochemical analyses. *The Journal of Comparative Neurology*, 473, 270–291.
- Mihalca, R., & Fica, S. (2014). The impact of obesity on the male reproductive axis. *Journal of Medicine and Life*, 7, 296–300.
- Misso, M. L., Murata, Y., Boon, W. C., Jones, M. E., Britt, K. L., & Simpson, E. R. (2003). Cellular and molecular characterization of the adipose phenotype of the aromatase-deficient mouse. *Endocrinology*, 144, 1474–1480.
- Monteagudo, P. T., Falcão, A. A., Verreschi, I. T., & Zanella, M. T. (2016). The imbalance of sex-hormones related to depressive symptoms in obese men. *The Aging Male*, 19, 20–26.
- Monteiro, R., Teixeira, D., & Calhau, C. (2014). Estrogen signaling in metabolic inflammation. *Mediators of Inflammation*, 2014, 615917.
- Morishima, A., Grumbach, M. M., Simpson, E. R., Fisher, C., & Qin, K. (1995). Aromatase deficiency in male and female siblings caused by a novel mutation and the physiological role of estrogens. *The Journal of Clinical Endocrinology and Metabolism*, 80, 3689–3698.

- Morton, G. J., & Schwartz, M. W. (2011). Leptin and the central nervous system control of glucose metabolism. *Physiological Reviews*, *91*, 389–411.
- Muschamp, J. W., & Hull, E. M. (2007). Melanin concentrating hormone and estrogen receptor-alpha are coextensive but not coexpressed in cells of male rat hypothalamus. *Neuroscience Letters*, *427*, 123–126.
- Mystkowski, P., Seeley, R. J., Hahn, T. M., Baskin, D. G., Havel, P. J., Matsumoto, A. M., Wilkinson, C. W., Peacock-Kinzig, K., Blake, K. A., & Schwartz, M. W. (2000). Hypothalamic melanin-concentrating hormone and estrogen-induced weight loss. *The Journal of Neuroscience*, *20*, 8637–8642.
- Ogawa, S., Chan, J., Gustafsson, J. A., Korach, K. S., & Pfaff, D. W. (2003). Estrogen increases locomotor activity in mice through estrogen receptor alpha: Specificity for the type of activity. *Endocrinology*, *144*, 230–239.
- Ohlsson, C., Hellberg, N., Parini, P., Vidal, O., Bohlooly-Y, M., Bohlooly, M., Rudling, M., Lindberg, M. K., Warner, M., Angelin, B., & Gustafsson, J. A. (2000). Obesity and disturbed lipoprotein profile in estrogen receptor-alpha-deficient male mice. *Biochemical and Biophysical Research Communications*, *278*, 640–645.
- Olefsky, J. M., & Glass, C. K. (2010). Macrophages, inflammation, and insulin resistance. *Annual Review of Physiology*, *72*, 219–246.
- Palin, S. L., McTernan, P. G., Anderson, L. A., Sturdee, D. W., Barnett, A. H., & Kumar, S. (2003). 17Beta-estradiol and anti-estrogen ICI: Compound 182,780 regulate expression of lipoprotein lipase and hormone-sensitive lipase in isolated subcutaneous abdominal adipocytes. *Metabolism*, *52*, 383–388.
- Pedersen, S. B., Bruun, J. M., Hube, F., Kristensen, K., Hauner, H., & Richelsen, B. (2001). Demonstration of estrogen receptor subtypes alpha and beta in human adipose tissue: Influences of adipose cell differentiation and fat depot localization. *Molecular and Cellular Endocrinology*, *182*, 27–37.
- Pedersen, S. B., Kristensen, K., Hermann, P. A., Katzenellenbogen, J. A., & Richelsen, B. (2004). Estrogen controls lipolysis by up-regulating alpha2A-adrenergic receptors directly in human adipose tissue through the estrogen receptor alpha. Implications for the female fat distribution. *The Journal of Clinical Endocrinology and Metabolism*, *89*, 1869–1878.
- Pellitero, S., Olaizola, I., Alastrue, A., Martínez, E., Granada, M. L., Balibrea, J. M., Moreno, P., Serra, A., Navarro-Díaz, M., Romero, R., & Puig-Domingo, M. (2012). Hypogonadotropic hypogonadism in morbidly obese males is reversed after bariatric surgery. *Obesity Surgery*, *22*, 1835–1842.
- Petersen, K. F., Dufour, S., Befroy, D., Lehrke, M., Hendler, R. E., & Shulman, G. I. (2005). Reversal of nonalcoholic hepatic steatosis, hepatic insulin resistance, and hyperglycemia by moderate weight reduction in patients with type 2 diabetes. *Diabetes*, *54*, 603–608.
- Phillips, I., Shah, S. I., Duong, T., Abel, P., & Langley, R. E. (2014). Androgen deprivation therapy and the re-emergence of parenteral estrogen in prostate cancer. *Oncol Hematol Rev*, *10*, 42–47.
- Popkin, B. M., Adair, L. S., & Ng, S. W. (2012). Global nutrition transition and the pandemic of obesity in developing countries. *Nutrition Reviews*, *70*, 3–21.
- Price, T. M., O'Brien, S. N., Welter, B. H., George, R., Anandjiwala, J., & Kilgore, M. (1998). Estrogen regulation of adipose tissue lipoprotein lipase – possible mechanism of body fat distribution. *American Journal of Obstetrics and Gynecology*, *178*, 101–107.
- Qiu, Y., Nguyen, K. D., Odegaard, J. I., Cui, X., Tian, X., Locksley, R. M., Palmiter, R. D., & Chawla, A. (2014). Eosinophils and type 2 cytokine signaling in macrophages orchestrate development of functional beige fat. *Cell*, *157*, 1292–1308.
- Remesar, X., Tang, V., Ferrer, E., Torregrosa, C., Virgili, J., Masanés, R. M., Fernández-López, J. A., & Alemany, M. (1999). Estrone in food: A factor influencing the development of obesity? *European Journal of Nutrition*, *38*, 247–253.
- Ribas, V., Drew, B. G., Le, J. A., Soleymani, T., Daraei, P., Sitz, D., Mohammad, L., Henstridge, D. C., Febbraio, M. A., Hewitt, S. C., Korach, K. S., Bensinger, S. J., & Hevener, A. L. (2011). Myeloid-specific estrogen receptor alpha deficiency impairs metabolic homeostasis and accel-

- erates atherosclerotic lesion development. *Proceedings of the National Academy of Sciences of the United States of America*, 108, 16457–16462.
- Ribas, V., Drew, B. G., Zhou, Z., Phun, J., Kalajian, N. Y., Soleymani, T., Daraei, P., et al. (2016). Skeletal muscle action of estrogen receptor  $\alpha$  is critical for the maintenance of mitochondrial function and metabolic homeostasis in females. *Science Translational Medicine*, 8, 334ra354.
- Riebe, C. J., Hill, M. N., Lee, T. T., Hillard, C. J., & Gorzalka, B. B. (2010). Estrogenic regulation of limbic cannabinoid receptor binding. *Psychoneuroendocrinology*, 35, 1265–1269.
- Rogers, N. H., Perfield, J. W., Strissel, K. J., Obin, M. S., & Greenberg, A. S. (2009). Reduced energy expenditure and increased inflammation are early events in the development of ovariectomy-induced obesity. *Endocrinology*, 150, 2161–2168.
- Roselli, C. E., Liu, M., & Hurn, P. D. (2009). Brain aromatization: Classic roles and new perspectives. *Seminars in Reproductive Medicine*, 27, 207–217.
- Ruan, H., Hachohen, N., Golub, T. R., Van Parijs, L., & Lodish, H. F. (2002). Tumor necrosis factor- $\alpha$  suppresses adipocyte-specific genes and activates expression of preadipocyte genes in 3T3-L1 adipocytes: Nuclear factor- $\kappa$ B activation by TNF- $\alpha$  is obligatory. *Diabetes*, 51, 1319–1336.
- Sanchis, D., Balada, F., del Mar, G. M., Virgili, J., Peinado, J., Monserrat, C., Fernández-López, J. A., Remesar, X., & Alemany, M. (1996). Oleoyl-estrone induces the loss of body fat in rats. *International Journal of Obesity and Related Metabolic Disorders*, 20, 588–594.
- Sanchis, D., Balada, F., Picó, C., Grasa, M. M., Virgili, J., Farrerons, C., Palou, A., Fernández-López, J. A., Remesar, X., & Alemany, M. (1997). Rats receiving the slimming agent oleoyl-estrone in liposomes (Merlin-2) decrease food intake but maintain thermogenesis. *Archives of Physiology and Biochemistry*, 105, 663–672.
- Schneider, G., Kirschner, M. A., Berkowitz, R., & Ertel, N. H. (1979). Increased estrogen production in obese men. *The Journal of Clinical Endocrinology and Metabolism*, 48, 633–638.
- Serrano, M., Grasa, M. M., Janer, G., Fernández-López, J. A., & Alemany, M. (2009). Oleoyl-estrone affects lipid metabolism in adrenalectomized rats treated with corticosterone through modulation of SREBP1c expression. *The Journal of Steroid Biochemistry and Molecular Biology*, 117, 15–22.
- Shahani, S., Braga-Basaria, M., & Basaria, S. (2008). Androgen deprivation therapy in prostate cancer and metabolic risk for atherosclerosis. *The Journal of Clinical Endocrinology and Metabolism*, 93, 2042–2049.
- Simerly, R. B., Chang, C., Muramatsu, M., & Swanson, L. W. (1990). Distribution of androgen and estrogen receptor mRNA-containing cells in the rat brain: an in situ hybridization study. *The Journal of Comparative Neurology*, 294, 76–95.
- Simpson, E. R. (1998). Genetic mutations resulting in estrogen insufficiency in the male. *Molecular and Cellular Endocrinology*, 145, 55–59.
- Simpson, E. R. (2003). Sources of estrogen and their importance. *The Journal of Steroid Biochemistry and Molecular Biology*, 86, 225–230.
- Simpson, E. R. (2004). Aromatase: Biologic relevance of tissue-specific expression. *Seminars in Reproductive Medicine*, 22, 11–23.
- Smith, E. P., Boyd, J., Frank, G. R., Takahashi, H., Cohen, R. M., Specker, B., Williams, T. C., Lubahn, D. B., & Korach, K. S. (1994). Estrogen resistance caused by a mutation in the estrogen-receptor gene in a man. *The New England Journal of Medicine*, 331, 1056–1061.
- Spencer, M., Yao-Borengasser, A., Unal, R., Rasouli, N., Gurley, C. M., Zhu, B., Peterson, C. A., & Kern, P. A. (2010). Adipose tissue macrophages in insulin-resistant subjects are associated with collagen VI and fibrosis and demonstrate alternative activation. *American Journal of Physiology Endocrinology and Metabolism*, 299, E1016–E1027.
- Stephens, J. M., Lee, J., & Pilch, P. F. (1997). Tumor necrosis factor- $\alpha$ -induced insulin resistance in 3T3-L1 adipocytes is accompanied by a loss of insulin receptor substrate-1 and GLUT4 expression without a loss of insulin receptor-mediated signal transduction. *The Journal of Biological Chemistry*, 272, 971–976.



- Stoffel-Wagner, B., Watzka, M., Schramm, J., Bidlingmaier, F., & Klingmüller, D. (1999). Expression of CYP19 (aromatase) mRNA in different areas of the human brain. *The Journal of Steroid Biochemistry and Molecular Biology*, 70, 237–241.
- Stout, M. B., Steyn, F. J., Jurczak, M. J., Camporez, J. G., Zhu, Y., Hawse, J. R., Jurk, D., Palmer, A. K., Xu, M., Pirtskhalava, T., Evans, G. L., de Souza, S. R., Frank, A. P., White, T. A., Monroe, D. G., Singh, R. J., Casacang-Verzosa, G., Miller, J. D., Clegg, D. J., LeBrasseur, N. K., von Zglinicki, T., Shulman, G. I., Tchkonja, T., & Kirkland, J. L. (2017). 17 $\alpha$ -Estradiol alleviates age-related metabolic and inflammatory dysfunction in male mice without inducing feminization. *The Journals of Gerontology Series A, Biological Sciences and Medical Sciences*, 72(1), 3–15.
- Straub, R. H. (2007). The complex role of estrogens in inflammation. *Endocrine Reviews*, 28, 521–574.
- Suganami, T., & Ogawa, Y. (2010). Adipose tissue macrophages: Their role in adipose tissue remodeling. *Journal of Leukocyte Biology*, 88, 33–39.
- Tagawa, N., Yuda, R., Kubota, S., Wakabayashi, M., Yamaguchi, Y., Kiyonaga, D., Mori, N., Minamitani, E., Masuzaki, H., & Kobayashi, Y. (2009). 17Beta-estradiol inhibits 11beta-hydroxysteroid dehydrogenase type 1 activity in rodent adipocytes. *The Journal of Endocrinology*, 202, 131–139.
- Takeda, K., Toda, K., Saibara, T., Nakagawa, M., Saika, K., Onishi, T., Sugiura, T., & Shizuta, Y. (2003). Progressive development of insulin resistance phenotype in male mice with complete aromatase (CYP19) deficiency. *The Journal of Endocrinology*, 176, 237–246.
- Tan, R. B., Guay, A. T., & Hellstrom, W. J. (2014). Clinical use of aromatase inhibitors in adult males. *Sex Medicine Review*, 2, 79–90.
- Thirumalai, A., Berkseth, K. E., & Amory, J. K. (2017). Treatment of hypogonadism: Current and future therapies. *F1000Research*, 6, 68.
- Titolo, D., Cai, F., & Belsham, D. D. (2006). Coordinate regulation of neuropeptide Y and agouti-related peptide gene expression by estrogen depends on the ratio of estrogen receptor (ER) alpha to ERbeta in clonal hypothalamic neurons. *Molecular Endocrinology*, 20, 2080–2092.
- Toda, K., Hayashi, Y., & Saibara, T. (2010). Deletion of tumor necrosis factor-alpha receptor type 1 exacerbates insulin resistance and hepatic steatosis in aromatase knockout mice. *Biochimica et Biophysica Acta*, 1801, 655–664.
- Toran-Allender, C. D., Tinnikov, A. A., Singh, R. J., & Nethrapalli, I. S. (2005). 17alpha-estradiol: A brain-active estrogen? *Endocrinology*, 146, 3843–3850.
- Tritos, N. A., Segal-Lieberman, G., Vezieridis, P. S., & Maratos-Flier, E. (2004). Estradiol-induced anorexia is independent of leptin and melanin-concentrating hormone. *Obesity Research*, 12, 716–724.
- Van Sinderen, M. L., Steinberg, G. R., Jørgensen, S. B., To SQ, Knowler, K. C., Clyne, C. D., Honeyman, J., Chow, J. D., Herridge, K. A., Jones, M. E., Simpson, E. R., & Boon, W. C. (2014). Hepatic glucose intolerance precedes hepatic steatosis in the male aromatase knockout (ArKO) mouse. *PLoS One*, 9, e87230.
- Vilà, R., Adán, C., Grasa, M. M., Masanés, R. M., Esteve, M., Cabot, C., Fernández-López, J. A., Remesar, X., & Alemany, M. (1999). Effect of food deprivation on rat plasma estrone fatty acid esters. *Diabetes, Obesity & Metabolism*, 1, 353–356.
- Viljanen, A. P., Iozzo, P., Borra, R., Kankaanpää, M., Karmi, A., Lautamäki, R., Järvisalo, M., Parkkola, R., Rönnemaa, T., Guiducci, L., Lehtimäki, T., Raitakari, O. T., Mari, A., & Nuutila, P. (2009). Effect of weight loss on liver free fatty acid uptake and hepatic insulin resistance. *The Journal of Clinical Endocrinology and Metabolism*, 94, 50–55.
- Wada, T., Ihunnah, C. A., Gao, J., Chai, X., Zeng, S., Philips, B. J., Rubin, J. P., Marra, K. G., & Xie, W. (2011). Estrogen sulfotransferase inhibits adipocyte differentiation. *Molecular Endocrinology*, 25, 1612–1623.
- Wang, H., & Ye, J. (2015). Regulation of energy balance by inflammation: Common theme in physiology and pathology. *Reviews in Endocrine & Metabolic Disorders*, 16, 47–54.

- Wang, F., Vihma, V., Soronen, J., Turpeinen, U., Hämäläinen, E., Savolainen-Peltonen, H., Mikkola, T. S., Naukkarinen, J., Pietiläinen, K. H., Jauhiainen, M., Yki-Järvinen, H., & Tikkanen, M. J. (2013). 17 $\beta$ -Estradiol and estradiol fatty acyl esters and estrogen-converting enzyme expression in adipose tissue in obese men and women. *The Journal of Clinical Endocrinology and Metabolism*, 98, 4923–4931.
- Weisberg, S. P., McCann, D., Desai, M., Rosenbaum, M., Leibel, R. L., & Ferrante, A. W. (2003). Obesity is associated with macrophage accumulation in adipose tissue. *The Journal of Clinical Investigation*, 112, 1796–1808.
- Wiehle, R., Cunningham, G. R., Pitteloud, N., Wike, J., Hsu, K., Fontenot, G. K., Rosner, M., Dwyer, A., & Podolski, J. (2013). Testosterone restoration by enclomiphene citrate in men with secondary hypogonadism: Pharmacodynamics and pharmacokinetics. *BJU international*, 112(8), 1188–1200.
- Wiehle, R. D., Fontenot, G. K., Wike, J., Hsu, K., Nydell, J., Lipshultz, L., & Group Z-CS. (2014). Enclomiphene citrate stimulates testosterone production while preventing oligospermia: A randomized phase II clinical trial comparing topical testosterone. *Fertility and Sterility*, 102, 720–727.
- Wing, R. R., & Group LAR. (2010). Long-term effects of a lifestyle intervention on weight and cardiovascular risk factors in individuals with type 2 diabetes mellitus: Four-year results of the Look AHEAD trial. *Archives of Internal Medicine*, 170, 1566–1575.
- Xu, H., Barnes, G. T., Yang, Q., Tan, G., Yang, D., Chou, C. J., Sole, J., Nichols, A., Ross, J. S., Tartaglia, L. A., & Chen, H. (2003). Chronic inflammation in fat plays a crucial role in the development of obesity-related insulin resistance. *The Journal of Clinical Investigation*, 112, 1821–1830.
- Xu, Y., Nedungadi, T. P., Zhu, L., Sobhani, N., Irani, B. G., Davis, K. E., Zhang, X., Zou, F., Gent, L. M., Hahner, L. D., Khan, S. A., Elias, C. F., Elmquist, J. K., & Clegg, D. J. (2011). Distinct hypothalamic neurons mediate estrogenic effects on energy homeostasis and reproduction. *Cell Metabolism*, 14, 453–465.
- Ye, J., & McGuinness, O. P. (2013). Inflammation during obesity is not all bad: Evidence from animal and human studies. *American Journal of Physiology Endocrinology and Metabolism*, 304(5), E466–E477.
- Zitzmann, M., Rohayem, J., Raidt, J., Kliesch, S., Kumar, N., Sitruk-Ware, R., & Nieschlag, E. (2017). Impact of various progestins with or without transdermal testosterone on gonadotropin levels for non-invasive hormonal male contraception: A randomized clinical trial. *Andrology*, 5(3), 516–526.
- Zumoff, B., Miller, L. K., & Strain, G. W. (2003). Reversal of the hypogonadotropic hypogonadism of obese men by administration of the aromatase inhibitor testolactone. *Metabolism*, 52, 1126–1128.