Estradiol acutely inhibits whole body lipid oxidation and attenuates lipolysis in subcutaneous adipose tissue: a randomized, placebo-controlled study in postmenopausal women

Lars Christian Gormsen1,2, Christian Høst1, Britta Eilersen Hjerrild1, Steen Bønløkke Pedersen1, Søren Nielsen1, Jens Sandahl Christiansen1 and Claus Højbjerg Gravholt1

1Medical Research Laboratories, Department of Endocrinology and Internal Medicine and 2Department of Nuclear Medicine and PET Centre, Aarhus University Hospital, Nørrebrogade, DK-8000 Aarhus C, Denmark

(Correspondence should be addressed to L C Gormsen at Department of Nuclear Medicine and PET Centre, Aarhus University Hospital; Email: lars.christian.gormsen@ki.au.dk)

Abstract

Context: Estradiol (E2) promotes and maintains the female phenotype characterized by subcutaneous fat accumulation. There is evidence to suggest that this effect is due to increased anti-lipolytic α2A-adrenergic receptors, but whether this requires long-term exposure to E2 or is an immediate effect is not clear.

Objective: To study acute effects of a single dose (4 mg) of 17β-E2 on regional and systemic lipolysis.

Methods: Sixteen postmenopausal women (age, 59 ± 5 years; weight, 67 ± 10 kg; and BMI, 24.8 ± 2.9) were studied in a crossover design: i) placebo and ii) 4 mg E2. Basal and adrenaline-stimulated regional lipolysis was assessed by microdialysis and substrate oxidation rates by indirect calorimetry. Tissue biopsies were obtained to assess lipoprotein lipase activity and mRNA expression of adrenergic, estrogen, cytokine, and vascular reactivity receptors.

Results: Acute E2 stimulation significantly attenuated catecholamine-stimulated lipolysis in femoral subcutaneous adipose tissue (interstitial glycerol concentration (micromole/liter) ANOVA time vs treatment interaction, \( P < 0.01 \)) and lipolysis in general in abdominal adipose tissue (ANOVA treatment alone, \( P < 0.05 \)). E2 also reduced basal lipid oxidation ((mg/kg per min) placebo, 0.58 ± 0.06 vs E2, 0.45 ± 0.03; \( P = 0.03 \)) and induced a significantly higher expression of anti-lipolytic α2A-adrenergic receptor mRNA (\( P = 0.02 \)) in skeletal muscle tissue as well as an upregulation of eNOS (NOS3) mRNA (\( P = 0.02 \)).

Conclusion: E2 acutely attenuates the lipolytic response to catecholamines in subcutaneous adipose tissue, shifts muscular adrenergic receptor mRNA toward anti-lipolytic α2A-receptors, decreases whole body lipid oxidation, and enhances expression of markers of vascular reactivity.

European Journal of Endocrinology 167 543–551

Introduction

Estradiol (E2) is the female sex steroid with effects on primary and secondary female sex organs. E2 also has direct antioxidant effects (1), changes vascular reactivity (2, 3), interacts with vascular smooth muscle (4, 5), and reduces the level of circulating cholesterol (6) and free fatty acids (FFAs) (7). Some of these effects are acute, taking place within minutes or hours (8), whereas the beneficial effects on lipid metabolism may be related to more prolonged effects of E2 on muscle and fat distribution. Thus, the reduced muscle power observed after menopause (9) is readily counteracted by female hormone therapy (HT) containing estrogens (10), which also prevents abdominal fat accumulation (11). Abdominal or visceral fat accumulation is associated with insulin resistance and dyslipidemia, notably elevated triglycerides (TGs), and high LDL-cholesterol (12).

Exactly how E2 modulates fat partitioning and redistribution is still not completely clear. Studies in transsexuals treated with E2 for a full year have demonstrated that lipolytic activity is reduced in both abdominal and femoral adipocytes during basal conditions (13). Likewise, 2 months of E2 treatment significantly reduces whole body lipolysis in postmenopausal women assessed by whole body palmitate turnover (14). This effect may be due to an increased number of anti-lipolytic α-adrenergic receptors and a decreased number of lipolytic β-adrenergic receptors.
(15), corroborated by the observation that noradrenaline-stimulated lipolysis in the abdominal region is attenuated when oral E2 is administered (16). A number of long-term replacement studies thus suggest that E2 to some extent modulates body composition via a gradual shift in catecholamine receptor composition favoring anti-lipolysis. However, E2 may act more acutely as demonstrated by Van Pelt et al. (17), who administered E2 i.v. and observed significantly diminished adipose tissue regional lipolysis assessed by microdialysis. This suggests that E2 not only acts via nuclear but also via membrane-bound receptors, which has indeed been demonstrated (18). However, to our knowledge, no group has hitherto studied whether this acute attenuation of regional tissue lipolysis is translated into decreased whole body lipid oxidation. In addition, no attempts to link regional microdialysis data to mRNA expression of lipid flux controlling catecholamine and estrogen receptors (ERs) have been done. The purpose of this study was therefore to study the effects of a single dose (4 mg) of E2 on regional adipose tissue lipolysis assessed by microdialysis and whole body lipid turnover assessed by indirect calorimetry. As an addition to previous studies, we aimed to link any such findings to changes in catecholamine receptor mRNA expression. It was our primary hypothesis that a single dose of E2 would result in significantly attenuated lipolysis, oxidation, and lipolytic catecholamine receptor mRNA expression.

Materials and methods

Subjects

Sixteen healthy postmenopausal women (age, 59 ± 5 years; weight, 67 ± 10 kg; and BMI, 24.8 ± 2.9) not on hormone replacement therapy were recruited through advertising. All had normal routine biochemistry and had been postmenopausal at least 1 year preceding the study. Subjects with FSH levels exceeding the detection limits of our assay were excluded. All subjects received oral and written information concerning the study before giving written informed consent. The protocol was approved by the Aarhus County Ethical Scientific Committee (#2002-0242). Study subjects were recruited over two periods with eight subjects recruited through 2005–2006 and another eight subjects recruited in 2008. Data on very LDL–TG (VLDL–TG) kinetics from the last eight subjects have previously been published (19).

Experimental protocol

The study was carried out as a single-blinded, placebo-controlled, randomized trial (Fig. 1). The participants were instructed not to perform any physical exercise or ingest alcohol 1 day before the start of the study. E2 (4 mg) or placebo was administered orally at t = −120 after an overnight fast (~ 10 h). Two intravenous catheters (Venflon; Viggo, Helsingborg, Sweden) were inserted in the antecubital vein of the right arm and in a dorsal vein of the right hand. The latter was placed in a heated box at 65 °C, allowing for arterialized blood samples to be drawn. At t = −90, microdialysis catheters were placed.

From t = 0 min and onward, blood samples were drawn every 30 min and analyzed for plasma glucose (PG), FFAs, cortisol, GH, insulin, C-peptide, and catecholamines. Sampling from the microdialysis catheters (interstitial fluid) commenced at t = 0 min, allowing for 60 min of equilibration to minimize the influence of local edema and hemorrhage. The sampling was performed every 30 min and continued until t = 330 min. From t = 120 – 240 min, adrenaline was added to the microdialysis perfusion fluid at a final concentration of 10 μm/l to enhance lipolysis locally (20).

From t = 240–330 min, adrenaline was infused i.v. at a rate of 0.15 nmol/kg per min (21). We aimed at limiting the increase in heart rate to no more than 50% during this study period, which was accomplished in all subjects.

Indirect calorimetry (Deltatrac Metabolic Monitor, Datex, Helsinki, Finland) with a ventilated hood at 40 l/min was performed, during the basal period (t = −30–0 min) and during the last 30 min of the systemically stimulated lipolysis (t = 300–330 min). Energy expenditure (EE), respiratory exchange ratio, and 24-h excretion of urea in urine were measured, and glucose, protein, and lipid oxidation were calculated (22).
**Tissue biopsies**

At time \( t = 210 \), a muscle biopsy was obtained from the vastus lateralis muscle with a Bergström biopsy needle under local anesthesia (1% lidocaine). A small incision was made through the skin and muscle sheath 15–20 cm above the knee. A total amount of ~200 mg muscle was aspirated, cleaned for blood (within 15 s), and snap-frozen in liquid nitrogen. Muscle biopsies were stored at ~80°C until analyzed. Immediately following the muscle biopsy, a subcutaneous fat biopsy from the periumbilical region was obtained by liposuction and snap-frozen in liquid nitrogen.

**Microdialysis**

After application of a local analgesic (Lidocaine), microdialysis catheters (CMA-60; CMA, Stockholm, Sweden) were inserted in subcutaneous adipose tissue in the periumbilical and femoral area. The microdialysis catheters have a molecular cutoff of 20 kDa and a membrane length of 30 mm and were perfused at a flow rate of 1 \( \mu \text{L/min} \) using CMA-107 perfusion pumps (CMA). We attempted to assess the relative recovery of interstitial glycerol by the internal reference method with \(^{3} \text{H}\)glycerol (23). However, adrenaline added to the perfusate introduced a dramatic variability in individual recovery rates (data not shown), interstitial glycerol concentrations were not corrected for relative recovery and may thus have been slightly underestimated. Per fusate and dialysate were counted using a Wallac 1450 liquid scintillation counter applying the Optiphase supermix scintillation fluid. Changes in interstitial glycerol concentration can be taken as an index of lipolysis (24, 25, 26).

**Adipose tissue blood flow**

Subcutaneous adipose tissue blood flow (ATBF) was assessed in the abdominal and femoral region by the local $^{133}$Xe washout method (27). In short, ~1 Mbq $^{133}$Xe was injected into the area of interest and based on the rate constant \( k \) of the washout curve, ATBF was calculated as $\text{ATBF} = k \times \lambda \times 100 \ (\text{ml/100 g per min})$, where \( \lambda \) is the tissue to blood partition coefficient for $^{133}$Xe at equilibrium; counts were collected every second and a straight line was fitted through the exponential points in a semilogarithmic diagram as a function of time. \( \lambda \) was calculated as \( \lambda = 0.22 \times \text{SFT} + 2.99 \), where SFT is the skin fold thickness of the abdominal adipose tissue (28).

**Lipoprotein lipase activity measurements**

Adipose tissue lipoprotein lipase (LPL) activity was determined essentially as described previously (29). Briefly, 200 mg adipose tissue was homogenized in a buffer containing 0.25 M sucrose, 1.0 mM K$_2$EDTA (pH 7.4) at 4°C, and the homogenate was centrifuged 20 min at 12,000 g at 4°C. The LPL activity in the postmitochondrial supernatant was determined by estimating the specific hydrolysis of \(^{14} \text{C}\)triolein after 60 min of incubation. FFAs were extracted from the incubation mixture as described previously (29) and measured by liquid scintillation counting.

Muscle LPL activity was measured in ~30 mg of the muscle biopsy. This was cut (on ice) into small pieces (3–5 mg) and placed in incubation tubes. The tissue was incubated in a heparin-containing (200 IU L$^{-1}$) medium with a serum-activated triolein emulsion with \(^{14} \text{C}\)-triolein as tracer and albumin as acceptor of released fatty acids. The mixture was incubated for 30 min on an ice bath and then for a further 120 min at 37°C in a shaking water bath. LPL activity was measured on the same day to eliminate the influence of day-to-day variation.

**Isolation of RNA**

Adipose tissue samples (200 mg) were homogenized in TRIzol reagent (Life Technologies, Inc.), and total RNA was extracted following the manufacturer’s protocol. RNA was quantified by measuring absorbency at 260 and 280 nm, and purity was assured by a ratio of 1.8 or higher. The integrity of the RNA was checked by visual inspection of the two ribosomal RNAs on an ethidium bromide-stained agarose gel.

**Real-time RT-PCR for mRNA analysis**

Reverse transcription was performed using random hexamer primers at 23°C for 10 min and 42°C for 60 min and was terminated by increasing the temperature to 95°C for 10 min, as described by the manufacturer (GeneAmp RNA PCR Kit from Perkin–Elmer Cetus, Norwalk, CT, USA). Then, PCR mastermix containing the specific primers and Taq DNA polymerase (HotStar Taq; Qiagen, Inc.) were added. Real-time quantitation of target gene (X0)-to-\( \beta \)-actin (R0) mRNA was performed with a SYBR-Green real-time PCR assay (Qiagen, Inc.) using an iCycler from Bio-Rad Laboratories as described previously (30). The X0 and R0 mRNA were amplified in separate tubes. The increase in fluorescence was measured in real time during the extension step. The threshold cycle (Ct) was calculated, and the relative gene expression was calculated essentially as described in the User Bulletin no. 2, 1997, from Perkin–Elmer. Briefly, the X0-to-R0 ratio in each sample before amplification was calculated as $X0/R0 = k \times 1/(2^{\Delta Ct})$, where $\Delta Ct$ is the difference between Ct-target and Ct-reference and $k$ is a constant, set to 1. All samples were amplified in duplicate. A similar setup was used for negative controls, except that the reverse transcriptase was omitted, and no PCR products were detected under these conditions. The following targets were measured: \( \alpha \)2A- receptor.
β1-receptor, β3-receptor, ERα, ERβ, uncoupling protein 2 (UCP2), UCP3, adiponectin, hormone-sensitive lipase (HSL), LPL, interleukin 6, vascular cell adhesion molecule 1, intercellular adhesion molecule, monocyte chemoattractant protein, and endothelial derived nitric oxide synthase (eNOS).

**Assays**

PG was analyzed in duplicate using the glucose oxidase method (Beckman Coulter, Palo Alto, CA, USA). Measurements were performed immediately during the study. Insulin was measured with an immunoassay (DAKO, Glostrup, Denmark). Serum FF A was determined by a colorimetric method employing a commercial kit (Wako Pure Chemical Industries, Neuss, Germany). Serum 17β-E2 was analyzed using a commercial ultrasensitive assay (Spectria Estradiol Sensitive RIA, Orion Diagnostica Espoo, Finland), with detection limits of 0.005 nmol/l. All samples from an individual patient were analyzed in the same assay. Adrenaline and noradrenaline were measured by HPLC (31). Glycerol in the microdialysis dialysate was measured in duplicate by an automated spectrophotometric kinetic enzymatic analyzer (CMA-600).

**Statistical analysis**

Results from blood samples (hormones and metabolites) are expressed as time-averaged values during the basal (0–240 min) and stimulated period (t = 240–330 min). To investigate the impact of E2 on regional lipolysis, we used a mixed model with fixed effect terms treatment (placebo or E2) and time and the interaction of time and treatment as the term of interest (time \times treatment). Subjects were included as random effects to account for within-subject correlation. All other between-treatment differences were assessed by Student’s t-test (parametric data) or Wilcoxon signed rank test (nonparametric data). P values < 0.05 were considered significant. Statistical analysis was performed using SPSS version 11 (SPSS Inc., IBM, Somers, NY, USA). Parametric data are presented as mean ± S.E.M. and nonparametric data as medians (range).

**Results**

**Hemodynamics**

Basal heart rate (pulse_{BASAL} (beats/min), 61 ± 2 (placebo) vs 61 ± 2 (E2); \(P = 0.57\)), systolic blood pressure (systolic_{BASAL} (mmHg): placebo, 127 ± 4 vs E2, 127 ± 3; \(P = 0.93\)), and diastolic blood pressure (diastolic (mmHg): placebo, 79 ± 3 vs E2, 79 ± 2; \(P = 0.77\)) was unaffected by E2. Likewise, the expected increase in heart rate and decrease in blood pressure induced by the systemic adrenaline infusion was similar regardless of treatment: (pulse_{SYSTEMIC} (beats/min): placebo, 73 ± 3 vs E2, 73 ± 2; \(P = 0.78\)), (systolic_{SYSTEMIC} (mmHg): placebo, 117 ± 4 vs E2, 117 ± 4; \(P = 0.95\)), and (diastolic_{SYSTEMIC} (mmHg): placebo, 68 ± 2 vs E2, 68 ± 2; \(P = 0.84\)).

**Circulating hormones**

Participants had low to undetectable E2 concentrations (0.08 ± 0.01 nmol/l) on the placebo study day (Fig. 2), while acute E2 resulted in an approximate fourfold rise in E2 concentrations with peak values occurring at \(t = 300\) min (0.35 ± 0.06 mmol/l). Adrenaline concentrations were low through basal and regionally stimulated lipolysis (adrenalin (pg/ml): placebo, 32.5 ± 3.4 vs E2, 35.6 ± 4.6; \(P = 0.54\)) and rose sharply to a plateau value (adrenalin (pg/ml): placebo, 308.6 ± 34.8 vs E, 300.9 ± 36.0; \(P = 0.83\)) after initiation of the adrenaline infusion. Noradrenaline concentrations were comparable on both study days and only increased modestly during the adrenaline infusion. Insulin levels tended to decrease through basal and regionally stimulated lipolysis on both study days (insulin (pmol/l): placebo, 22.5 ± 2.3 vs E2, 23.6 ± 2.6; \(P = 0.55\)) with a similar increase in response to elevated glucose levels observed during the adrenaline infusion (insulin (pmol/l): placebo, 28.5 ± 3.1 vs E2, 28.6 ± 2.8; \(P = 0.97\)).

**Metabolites**

FFA levels were similar on both study days through the basal and regionally stimulated period (FFA (µmol/l)):
placebo, 583 ± 33 vs E2, 575 ± 34; P = 0.86; Fig. 2). Adrenaline infusion doubled FFA levels within 30 min to ~1.200 μmol/l with a subsequent gradual decrease to ~900 μmol/l at t = 330 min. Blood glucose concentrations tended to decrease slightly through the basal and regionally stimulated period and rose sharply after initiation of the adrenaline infusion (Fig. 2). No significant differences in glucose levels between treatment days were observed.

**Regional lipolysis**

Three distinct patterns of adrenaline-induced lipolysis were observed (Fig. 3): i) in muscle, basal interstitial glycerol concentrations, and thus lipolysis, were unaffected by E2 and the regional and systemic adrenaline stimulation elicited similar increases in interstitial glycerol concentrations (micromole/liter; repeated measurements ANOVA (RM-ANOVA; time vs treatment), P = NS). ii) In femoral adipose tissue, a similar lack of effect was observed in the basal period, whereas the lipolytic response to adrenaline-stimulated lipolysis was significantly attenuated when subjects were treated with E2 (RM-ANOVA (time vs treatment), P = 0.01). iii) In abdominal adipose tissue, by contrast, interstitial glycerol concentrations were lower after E2 treatment already during the basal period and remained significantly subdued during local adrenaline and systemic stimulated lipolysis (RM-ANOVA (treatment), P < 0.05). This anti-lipolytic effect was not enhanced by adding epinephrine to the perfusate (RM-ANOVA during the regional period (time vs treatment), P = 0.34).

**Substrate oxidation (indirect calorimetry)**

During basal conditions, E2 treatment significantly decreased whole body lipid oxidation rates (LIPOXbasal (mg/kg per min): placebo, 0.58 ± 0.06 vs E2, 0.45 ± 0.03; P = 0.03; Fig. 4). As expected, glucose oxidation was increased, albeit not significantly (GOXbasal (mg/kg per min): placebo, 1.31 ± 0.11 vs E2, 1.48 ± 0.10; P = 0.10). The adrenaline infusion elicited an immediate ~20% increase in EE regardless of treatment (data not shown), which could be entirely attributed to increased lipid oxidation. However, during systemic adrenaline stimulation, no difference was observed in neither lipid (LIPOXsystemic (mg/kg per min): placebo, 0.87 ± 0.09 vs E2, 0.87 ± 0.08; P = 0.98) nor glucose (GOXsystemic (mg/kg per min): placebo, 1.06 ± 0.19 vs E2, 1.13 ± 0.14; P = 0.60) oxidation (Fig. 5).

Basal total EE tended to decrease during E2 treatment (EEbasal (kcal/24 h): placebo, 1297 ± 51 vs E2, 1237 ± 40; P = 0.06), whereas this was not observed during adrenaline-stimulated conditions (EESystemic (kcal/24 h): placebo, 1472 ± 56 vs E2, 1504 ± 57; P = 0.31).

**LPL activity and mRNA expression**

E2 treatment resulted in a trend toward reduced LPL activity in skeletal muscle (~26%, P = 0.09) whereas this was not the case in adipose tissue. No convincing trends were observed in LPL mRNA levels in muscle tissue or fat.

**Catecholamine receptor gene expression**

E2 resulted in significantly increased anti-lipolytic α2-adrenergic receptor mRNA in muscle (Fig. 5B) and also tended to increase lipolytic β1-adrenergic receptor mRNA in that tissue (D). However, we were unable to detect any measurable effect of E2 on the same receptor mRNA in adipose tissue (Fig. 5A and C).
Markers of vascular reactivity (ATBF and eNOS mRNA)

During basal conditions, ATBF in both the femoral (ATBF\textsubscript{BASAL} (ml/100 g per min): placebo, 1.01 ± 0.18 vs E\textsubscript{2}, 1.04 ± 0.13; \textit{P} = 0.90) and the abdominal (ATBF\textsubscript{BASAL} (ml/100 g per min): placebo, 0.93 ± 0.11 vs E\textsubscript{2}, 0.84 ± 0.13; \textit{P} = 0.58) region was comparable. However, during systemic adrenaline infusion, E\textsubscript{2} treatment resulted in significantly diminished ATBF in the abdominal region (ATBF\textsubscript{SYSTEMIC} (ml/100 g per min): placebo, 1.37 ± 0.15 vs E\textsubscript{2}, 0.98 ± 0.16; \textit{P} = 0.01), whereas no such effect was observed in the femoral region (ATBF\textsubscript{SYSTEMIC} (ml/100 g per min): placebo, 1.50 ± 0.24 vs E\textsubscript{2}, 1.64 ± 0.17; \textit{P} = 0.44; Fig. 6).

In muscle, E\textsubscript{2} significantly increased eNOS (NOS3) mRNA expression (\textit{P} = 0.02). No significant effect was observed in adipose tissue.

Discussion

The principal results from this study show that a single dose of E\textsubscript{2} in postmenopausal women resulted in significant and immediate metabolic responses: i) the lipolytic response to local catecholamine stimulation in subcutaneous femoral adipose tissue was attenuated; ii) overall lipolysis was attenuated in subcutaneous abdominal adipose tissue; iii) an immediate shift in muscle adrenergic receptor expression toward anti-lipolytic \(\alpha\text{2A}\)-receptors occurred; iv) whole body fuel combustion shifted from lipid oxidation toward glucose consumption and a trend toward diminished LPL activity and thus extraction of lipids from circulating lipoproteins was observed; and v) finally, E\textsubscript{2} altered markers of vascular reactivity by stimulating eNOS mRNA expression in muscle tissue and decreasing adrenaline-stimulated ATBF in the abdominal region.

Menopause causes an extensive array of modulations in the typical female fat distribution, most notably a shift in fat depots from the lower body and subcutaneous depots to the upper body and visceral depots (32). Female sex HT abolishes this potentially deleterious effect of menopause and the accompanying decrease in estrogen levels (11), but whether this effect of E\textsubscript{2} on lipid metabolism is indirect or direct is not obvious. Adipocytes express both \(\alpha\)- and \(\beta\)-ERs (33) and long-term E\textsubscript{2} treatment results in a shift in adrenergic receptor composition increasing the number of anti-lipolytic \(\alpha\text{2A}\)-receptors (15). Thus, the effect of E\textsubscript{2} on lipid metabolism and hence on body composition

![Figure 4](Image)

**Figure 4** Substrate oxidation rates. (A) Lipid oxidation. E\textsubscript{2} administration significantly decreased basal lipid oxidation. (B) Glucose oxidation. No difference was observed between placebo and E\textsubscript{2}. All error bars are ± S.E.M., \(n = 15\) (one subject suffered from claustrophobia and could not cooperate). ‘Basal’ refers to \(t = 60\) to 120 min whereas ‘systemic’ refers to systemic stimulation with adrenaline from \(t = 240\) to 330 min.

![Figure 5](Image)

**Figure 5** Anti-lipolytic \(\alpha\text{2A}\)- and \(\beta1\)-receptor mRNA expression. Median values are represented by vertical lines as appropriate, \(n = 14\) (two subjects did not wish to have muscle biopsies taken). All units are arbitrary units (AU). Adipose tissue was obtained from the periumbilical region.
Adipocyte function is tightly regulated by a range of hormones and enzyme systems. Hyperinsulinemia favors TG accumulation through inhibition of the HSL, whereas catecholamine stimulation through adrenergic β1- and β2-receptors stimulates lipolysis via increased HSL activity. Countering the lipolytic effects of adrenergic β-receptors, stimulation of the α2A-receptor initiates a cascade blocking adenylate cyclase and ultimately resulting in inhibition of the HSL mimicking the effects of insulin (35). The ratio of lipolytic β-receptors to anti-lipolytic α-receptors is shifted by exposure to E2 depending on the location of the fat depot: in visceral fat, E2 has no detectable effect on this ratio, whereas a change toward anti-lipolytic α-receptors is observed in subcutaneous fat depots (15). This could suggest that the decline in estrogen observed after menopause promotes lipolysis and contributes to reduced subcutaneous adipose tissue. Data presented here demonstrate that in skeletal muscle a shift toward anti-lipolytic α2A-receptors takes place on mRNA level within hours after E2 exposure and in adipose tissue the same trend was observed.

In line with the findings of most (14, 36, 37, 38, 39), but not all (40), previous studies, whole body lipid oxidation was significantly decreased in our volunteers during E2 treatment. However, whereas previous studies have been designed to study more long-term effects of estrogens with typical treatment periods lasting 1–12 months, this is to our knowledge the first study in humans reporting immediate effects of estrogen on lipid oxidation. Interestingly, animal studies have indicated that E2 administered for brief periods results in significantly reduced hepatic carnitine palmitoyltransferase 1 (CPT1) mRNA expression (41) and thus reduces lipids transported into mitochondria for oxidation. Our results suggest that hepatic and/or peripheral lipid oxidation is effectively reduced within hours after E2 exposure, an effect that must be largely independent of gene up or down regulation.

Somewhat to our surprise, E2 reduced the known stimulatory effect of systemic adrenaline infusion on ATBF (42). However, as E2 convincingly reduces lipid oxidation and subcutaneous lipolysis, it is intuitively appealing that it should also reduce ATBF to regional fat depots. E2 treatment was also associated with a significant increase in eNOS mRNA expression in muscle, an effect that has been demonstrated before in animal and cell studies (43, 44). This may serve to further divert blood from adipose tissue toward muscle.

The data presented herein demonstrate that E2 has immediate and therefore most likely nongenomic effects on lipid metabolism. In summary, E2: i) attenuates the lipolytic response to adrenaline in subcutaneous femoral adipose tissue and overall lipolysis in subcutaneous abdominal adipose tissue; ii) inhibits basal whole body lipid oxidation; iii) upregulates anti-lipolytic α2A-receptor mRNA in muscle; and iv) reduces the stimulatory effect of adrenaline on ATBF.
Declaration of interest
I. C. Gormsen, B. E. Hjerrild, S. B. Pedersen, and S. Nielsen have no disclosures. C. H. Gravholt has received lecture fees from Novo Nordisk. J. S. Christiansen has served as a consultant and received lecture fees from Novo Nordisk, Pfizer, and Ipsen.

Funding
The study was supported by grants from the Danish Health Research Council, grant number 22-01-0395, and the Novo Nordisk Foundation.

Author contribution statement
All studies were performed at The Medical Research Laboratories, Aarhus University Hospital, Denmark. I. C. Gormsen designed the experiments, performed metabolic studies, collected data, interpreted data, and wrote the manuscript. C. H. Gravholt performed metabolic studies and collected data. B. E. Hjerrild performed metabolic studies and collected data. S. B. Pedersen collected and interpreted data and revised the manuscript. J. S. Christiansen interpreted data and revised the manuscript. S. Nielsen collected data, interpreted data, and revised the manuscript. C. H. Gravholt conceived the experiment, designed the study, collected and interpreted data, and revised the manuscript.

Acknowledgements
The authors thank Annette Mengel for excellent technical assistance. Roche Diagnostics kindly donated the microdialysis catheters.

References
10. Phillips SK, Rook KM, Siddle NC, Bruce SA & Wolejdo RC. Muscle weakness in women occurs at an earlier age than in men, but strength is preserved by hormone replacement therapy. Clinical Science 1993 84 95–98.
Acute effects of estrogen in humans

551


Received 14 May 2012

Revised version received 17 July 2012

Accepted 6 August 2012

www.eje-online.org