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The acute effects of diet-induced energy restriction on physical activity energy expenditure and basal metabolic rate in men and women with overweight and obesity

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ABSTRACT

Introduction: Reductions in physical activity energy expenditure (PAEE) and basal metabolic rate (BMR) have been proposed as factors that may hinder diet-induced body mass loss. Although diet-mediated changes in PAEE and BMR are subject to large inter-individual variability, research investigating the impact of sex on diet-induced modulation of PAEE and BMR is lacking. Therefore, this study examined the effect of a diet-induced energy restriction on PAEE and BMR in non-exercising overweight and obese men and women.

Methods: Eleven women (Age: 25 ± 7 yr; BMI: 29.7 ± 4.2 kg/m^2) and eight men (Age 29.6 ± 4.0 yr; BMI: 29.7 ± 4.0 kg/m^2) completed a 29-day investigation. Assessment of physical activity (PA) (PAEE and step count), BMR, body composition, systolic (SBP) and diastolic (DBP) blood pressure and fasting blood glucose (FBG) occurred on days 1, 8, 15, 22 and 29. Between days 15–22, participants consumed a liquid diet formula equivalent to 50% of their total daily energy expenditure (TDEE). The effects of time, sex and their interaction on all variables were assessed through a two-way mixed model ANOVA.

Results: Both men and women achieved a modest 3% body mass loss at the end of the intervention week. An effect of time was detected for body mass ($p < 0.001$), BMI ($p < 0.001$), body fat % ($p = 0.001$), SBP ($p = 0.007$), DBP ($p = 0.033$) and BG ($p < 0.001$). There was a time and sex interaction for body mass ($p = 0.002$), BMI ($p = 0.002$) and body fat % ($p = 0.043$). Sex differences were only present for body fat % ($p = 0.001$) and BMR ($p < 0.001$). No main or interaction effects were present for PAEE and step count.

Conclusion: In the present study, a 7-day diet-induced energy restriction of 50% did not elicit compensatory changes in PAEE and BMR in overweight and obese men and women. Findings suggest that it may be a viable short-term strategy to produce initial reductions in body mass and body fat %, with improvements in fasting blood glucose and resting blood pressure.

1. Introduction

Obesity is a complex and multifactorial disease characterised by abnormal or excess body fat, which is associated with several pathological conditions such as hypertension, type 2 diabetes and certain forms of cancer [1]. In addition, obesity is a serious financial burden costing approximately 27 billion to the wider society in the UK [2]. Diet-induced energy restriction (ER) is a common approach to induce body mass loss, however, interventions adopting diet-induced ER alone report body mass losses 12–44% lower than predicted (Yoo, 2019). This is because energy balance is a non-linear (dynamic) process, and an attempt to reduce energy intake (EI) often results in an unintended change in one or more components of total daily energy expenditure (TDEE), thus ultimately altering the rate of body mass loss [3]. Indeed, when ER is induced, the initial body mass loss is accompanied by metabolic and behavioural changes that manifest primarily in basal metabolic rate (BMR) and physical activity energy expenditure (PAEE) [4]. [5]; showed reductions in BMR (−48 kcal/day) after 3 days of ER

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using a very low-energy diet (VLED) providing 670 kcal and 550 kcal/day for men and women, respectively. In the same study, disproportionate changes were observed when BMR was separately analysed for biological sex. In fact, after adjusting for fat-free mass (FFM) and fat mass (FM), 3 days of ER produced a 24 kcal/day greater decrease of BMR in women than in men [5]. Another study in young healthy men showed a significant decrease in BMR (−70 kcal/day) after just 3 days of 50% diet-induced ER that continued after 7 days [6]. Nevertheless, this drop in BMR started to plateau after 21-days, when a 5% reduction in body mass was achieved.

In addition to its effects on BMR, diet-induced ER also appears to have an impact on PAEE [7]. reported that 4 weeks of 50% diet-induced ER resulted in a 4–11% reduction in BMR accompanied by concomitant decreases in PAEE, that almost entirely explained the collective drop in TDEE. Similarly [8], induced a 20% ER via diet, which after 20 days resulted in reduced BMR and PAEE of 99 kcal/day and 198 kcal/day, respectively. Comparable findings were observed in longer-term trials, such as [9] who reported a 220 kcal/day decrease in PAEE after 8 weeks of VLED (500 kcal/day) in obese men and women. Nonetheless, PAEE returned to baseline when energy balance was re-established.

In a randomised control trial of 105 adults [10], used doubly-labelled water and accelerometery, a gold-standard combination technique, to assess the effects of 10% and 30% ER on PAEE. Although biological sex and age were not associated with the effect of ER on PAEE, a 200 kcal/day reduction in PAEE was observed after 12 weeks of 30% ER. Moreover, in their 'weight clamping' experiment [11], observed a 15% decrease in TDEE with underfeeding in obese women. As participants were not taking part in any volitional exercise, changes in TDEE were believed to be largely attributed to changes in PAEE. Similarly [12], found reductions in BMR and PAEE which accounted for a 350 kcal/day drop of TDEE after 12 weeks of diet-induced ER.

Even compared to exercise, diet-induced ER appears to provoke the greatest compensation in PAEE. Where ER was induced via diet alone, diet plus low-intensity exercise or diet plus moderate-intensity exercise, the greatest compensation in PAEE (−30%) was observed in the diet-only group [13]. Moreover, the magnitude of body mass regain in this study was greater in participants who experienced larger reductions in TDEE during ER. Decreases in PAEE were also reported by Martin and colleagues (1985), where 12 weeks of 25% diet-induced ER and LED (890 kcal/day) yielded 12% and 20% drops in PAEE, respectively. Collectively, components of TDEE, particularly BMR and PAEE, change in response to perturbations of energy balance. However, these changes were more pronounced during the first phase of ER [14].

An increasing body of evidence suggests that faster rates of initial body mass loss, and hence higher sustained EE, is positively associated with successful body mass loss and long-term maintenance [15]. Moreover, men have been shown to display greater reductions in body mass than women, even after adjustment for differences in body mass percentage [16]. However, there is a paucity of research examining the sex-mediated differences of PAEE and BMR in response to acute diet-induced ER [14].

The present study aimed to investigate whether 7 days of diet-induced ER influenced PAEE, and BMR in men and women who were overweight or obese. It was hypothesised that acute diet-induced ER would result in lowered BMR and PAEE, and that this compensatory response would be relatively greater in women than in men.

2. Methods

2.1. Experimental design

This study used a time series design, with an initial 2-week control period to investigate the effect of 1-week of diet-induced ER (50% of TDEE) on PAEE and BMR in men and women who were overweight or obese. Participants visited the institution's laboratory on five separate occasions over four weeks (Fig. 1), at the start and mid 2-week control period (days 1 & 8), start of 1-week intervention (day 15) and start and end of 1-week post intervention period (days 22 & 29). Assessment included body composition, fasting blood glucose, blood pressure and BMR. The 7-day period between each visit was selected to match the time frame of the liquid-based diet intervention and the usual time used to assess physical activity in the free-living [17]. Consequently, this study used hip and wrist-worn tri-axial accelerometers to determine total amount of steps and PAEE measured in 7-day blocks between study days 1 and 29 and 8 and 29, respectively (Fig. 1).

2.2. Participants

A total of 25 overweight or obese adults volunteered to participate in the study. Six participants (4 men and 2 women) withdrew from the study prior to completion. Two men were unable to visit on the assessment days; and two women and two men due to nausea from the liquid diet. Therefore, a total of 11 women and 8 men completed the study and were included in the analysis.

Recruitment was carried out via social media, word of mouth and information leaflets. Inclusion criteria included: 1) aged 18–40 years; 2) BMI 25–40 kg/m^2; 3) engage in ≤1 session of volitional exercise per week; 4) healthy (i.e. no existing pathological conditions).

Participants were fully informed both verbally and in writing about the study and given 7 days to decide whether to participate. A Physical Activity Readiness Questionnaire (PARQ) was completed to ensure there were no underlying health issues. The study was approved by Abertay University School of Health and Applied Sciences Research Ethics Committee (EMS1014), and all and all participants provided written informed consent.

2.3. Experimental procedures

To ensure consistency, participants visited the laboratory between 7:00 and 9:00 following an overnight fast from food, caffeine, nicotine and any caloric beverage 12 h prior to testing but allowed water ad libitum [18]. Participants were instructed to avoid vigorous exercise 24 h prior to testing to ensure accurate measurement of BMR [19]. Upon arrival, participants were asked to void their bladder prior to commencing testing. Compliance was verified by verbal self-reporting to the investigator, to ensure accurate measurement of BMR, body composition, blood pressure and fasting blood glucose [20].

Anthropometry**:** On day 1, stature was measured to the nearest 0.1

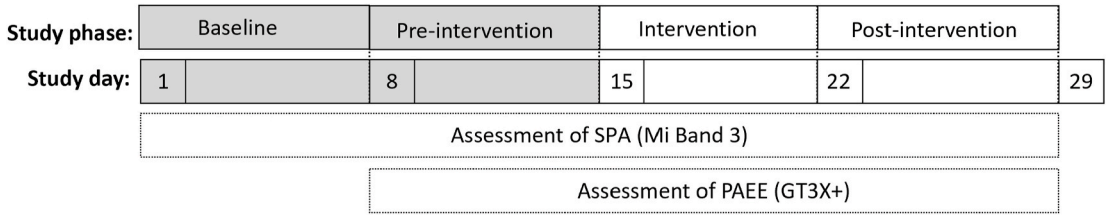

Fig. 1. Study timeline overview. Grey shaded area represents the control period used to assess PAEE Study days 1, 8 and 15 were used to determine baseline values before the intervention.

cm using a stadiometer (SECA 216, SECA, Hamburg, Germany) in the Frankfort horizontal plane (Bryan & Green, 2013). The remaining anthropometric variables were measured during all laboratory visits. To ensure an accurate and consistent reading of body composition via the leg-to-leg bioelectrical impedance scale (SC-330ST, Tanita Europe, Amsterdam, the Netherlands), participants were asked to void their bladder and then remove excess clothing prior to recording body mass (kg) and body fat (%) to the nearest 0.1 respective unit [21].

Blood Glucose: Resting blood pressure as SBP, DBP and pulse pressure, were recorded twice on the participant's non-dominant arm using an automated oscillomettric blood pressure monitor (DSK-1031, Nissei Healthcare, Henfield, UK). The first blood pressure measurement was taken after the participant was seated comfortably and silently for 5 min, with their back supported, feet on the floor, arm supported in the horizontal position on a table, with the middle of the blood pressure cuff on the participant's upper arm at the heart level. The second measurement was taken immediately after the first was completed, and the measurement with the lower pulse pressure was then used for analysis [20].

Fasting Blood Glucose: was determined via fingertip blood samples (Freestyle Lite, Abbott Diabetes Care Inc., Alameda, USA) from the tip of the index finger using an Accu-check single use lancet (Roche Diagnostics, UK) and pressure applied to the finger to draw the blood [22]. The initial drop was discarded, and the second drop was taken for analysis [23].

Basal Metabolic Rate: was determined by breath-by-breath analysis using an open-circuit indirect calorimetry (MetaMax 3B, Cortex Biophysik, Leipzig, Germany) [24]. The participant rested still in a comfortable supine position in a quiet environment for 30 min. Full calibration of the metabolic cart was carried out in accordance with the manufacturer's guidelines using a 3-L calibration syringe, pressure calibration with a digital barometer (Barometer GA690, Castle Group, UK) and gas calibration using a 1.2 L bottle with 15% oxygen (O2), 5% and carbon dioxide (CO2), in nitrogen (N2). Next BMR was measured for 15–20 min and the average VO2 and VCO2 values from the last 10 min were used for analysis [19,23]. This method was based on the systematic review by Ref. [24] which determined the optimal conditions for obtaining reliable measures of BMR by indirect calorimetry. Due to its high prevalence in human studies, Weir's equation with dismissed protein oxidation was used to calculate BMR [21].

$$\text{BMR (kcal/day)} = (3.941 \text{ x VO2 (ml/min)} + (1.106 \text{ x VCO2 (ml/min)}) \text{ x } 1.44)$$

Physical Activity Indices: Step count was measured from day 1 to day 29 using a tri-axial accelerometer (Mi Band 3, Xiaomi, Beijing, China) which had an embedded heart rate sensor, and was worn on the wrist of the dominant arm. The first iteration of this activity tracker has been shown to be an accurate and valid alternative to more costly accelerometers which are validated in clinical research [25]. Heart rate sampling frequency (Mi Band 3, Xiaomi, Beijing, China) was set to 60s via the Android application Mi Fit (Xiaomi, Beijing, China).

To measure PAEE, participants wore a second tri-axial accelerometer (ActiGraph GT3X+, Florida, USA) on the right hip from day 8–29 (Sasaki, John & Freedson, 2011). Participants were advised to wear the accelerometers continuously except during their sleep and activities which would submerge the accelerometers in water. A day was considered valid only when the accelerometers were worn for at least 10 h between 0700 and 2300 [26]. In addition, a phase (week) was considered valid only when it was comprised of four or more valid days [27]. The ActiGraph accelerometer was set-up with 60 s sampling epochs which were collected at a 30 Hz sample rate, and the Freedson VM3 combination algorithm was used to estimate PAEE from the vector magnitude counts per min of the three axes [28]. PAEE data from each phase was averaged and presented as kcal/day. The method for the ActiGraph GT3X + accelerometer was based on the systematic review by Ref. [27] which provided practical considerations such as optimal placement, sampling frequency, epoch length and day/week validity for adults.

Diet-Induced Energy Restriction: The methods to assess TDEE require quantification of all its components, namely BMR, TEF and PAEE. To calculate participant's average pre-intervention TDEE, BMR and TEF from study days 1, 8 and 15 were averaged and summed with daily average of PAEE from the Pre-intervention phase. TEF was assumed as a generic 10% value of TDEE [29]:

$$\text{TEF}\left(\frac{\text{kcal}}{\text{day}}\right) = (\text{BMR} + \text{PAEE}) \text{ x } 0.1$$

$$\text{TDEE(kcal / day)} = \text{BMR} + \text{TEF} + \text{PAEE}$$

During the intervention period (days 15–21), participants were given a 7-day supply of the formula-based liquid diet (Meal Replacement, MyProtein, UK) that provided a macronutrient breakdown of 38% protein, 38% carbohydrates, 15% fats and 9% fibre [5]. Participants were asked to use the formula-based liquid diet as their only source of energy intake resulting in a 50% energy restriction in relation to participant's mean pre-intervention TDEE. The formula-based diet was weighed by the investigator using a commercially available kitchen scale (Salter, HoMedics Group Ltd, Kent, UK) and individually packaged to provide the exact energy value each day during the intervention period. No recommendation was given regarding meal pattern or meal frequency. Participants were allowed to consume any very-low or non-caloric beverage such as black coffee, green tea or soft drinks with no added sugar.

Study Compliance Survey: To gather insights regarding the rate of compliance to the study procedures, at the end of data collection an anonymous survey was sent to participants. The survey comprised of 4 closed questions, which served to evaluate the dietary compliance to the liquid diet and participant's conditions on each testing day.

2.4. Statistical analyses

Statistical analyses were performed using the statistical package for the social sciences software for windows (SPSS 24.0, IBM, Chicago, IL, USA). Data were checked for normality using histograms and the Shapiro-Wilk test. Levene's and Mauchley's test were respectively used to check for homogeneity of variance and sphericity. When the latter was violated ($p \geq 0.05$) the Greenhouse Geiser correction was used [24]. A two-way (Time x Sex) mixed model ANOVA was used to assess the effects of time, sex and their interaction on all variables during the control period (except PAEE assessed by ActiGraph which only included 1 week of control) as well as across all periods (i.e. control, intervention and post-intervention). Pairwise comparisons were performed using the Bonferroni correction [30]. As BMI was not normally distributed, an adjusted rank-transformation was applied to these data [29]. All data are presented as Mean ± Standard Deviation (M±SD) (95% confidence intervals: lower, upper) unless specified, and mean differences (MD) provided when significant main effects were found. Partial eta squared (η_p^2) effect sizes were interpreted as 0.01 small, 0.06 moderate and 0.14 as large whilst Cohen's effect size (d) was defined as 0.2 small, 0.5 moderate, 0.8 large. Significance level was set at $p < 0.05$.

3. Results

3.1. Control period (Day 1–14)

The control period served to evaluate the consistency of the measurements and to compare the physical characteristics between men and women (Table 1).

Men had lower body fat ($F(1,17) = 16.007$; MD = -10.833; 95% CI: 16.55 to −5.120; $p < 0.001$; $d = 2.0$) and higher BMR ($F(1,17) = 13.633$; MD = -347.594; CI: −546.139 to −148.959; $p < 0.002$; $d = 1.6$) than women. In addition, there was a main effect of time for body fat ($F(2,34) = 4.674$; $p = 0.027$; $\eta_p 2 = 0.562$) between day 1 and day 8 (MD: −0.618;

Table 1
Anthropometric, metabolic and physiological measures during control period.

	Day 1	Day 8	Day 15	Statistical significance of effect of:		
Variable	Mean ± SD	Mean ± SD	Mean ± SD	Time	Sex	Time x Sex
Body mass (kg)	84.0 ± 13.3	83.8 ± 13.5	83.7 ± 13.5	0.373	0.061	0.504
Men	90.7 ± 13.5	90.6 ± 14.1	90.2 ± 14.3	/	/	/
Women	79 ± 11.4	78.9 ± 11.1	78.9 ± 11.1	/	/	/
BMI (kg/m2)	**29.6 ± 3.7**	**29.6 ± 4.0**	**29.6 ± 3.9**	**0.912**	**0.726**	**0.390**
Men	29.6 ± 3.7	29.6 ± 4.1	29.5 ± 4.2	/	/	/
Women	29.7 ± 4.1	29.6 ± 4.6	29.6 ± 3.9	/	/	/
Body fat (%)	**33.6 ± 7.9**	**33.0 ± 8.0**	**33.4 ± 7.8**	**0.027***	**0.001***	**0.290**
Men	27.4 ± 5.4	26.6 ± 5.7	27.3 ± 6	/	/	/
Women	38.1 ± 6.3	37.8 ± 6	37.9 ± 5.5	/	/	/
LBM (kg)	**52.7 ± 9.1**	**53.1 ± 9.4**	**52.6 ± 8.9**	**0.022***	**<0.001***	**0.026***
Men	62.2 ± 5.7	62.7 ± 5.9	61.8 ± 5.9	/	/	/
Women	45.9 ± 2.1	46.1 ± 2.3	46.1 ± 2.3	/	/	/
BMR (kcal/24h)	**1489 ± 293**	**1429 ± 257**	**1476 ± 284**	**0.232**	**0.002***	**0.935**
Men	1685 ± 317	1627 ± 235	1686 ± 237	/	/	/
Women	1347 ± 176	1285 ± 163	1323 ± 211	/	/	/
SBP (mm Hg)	**138 ± 23**	**135 ± 16**	**131 ± 18**	**0.068**	**0.108**	**0.252**
Men	148 ± 16	140 ± 13	138 ± 21	/	/	/
Women	130 ± 25	132 ± 17	125 ± 15	/	/	/
DBP (mm Hg)	**82 ± 14**	**81 ± 11**	**82 ± 13**	**0.323**	**0.675**	**0.594**
Men	83 ± 9	80 ± 8	81 ± 18	/	/	/
Women	81 ± 17	81 ± 13	76 ± 9	/	/	/
PP (mm Hg)	**71 ± 12**	**68 ± 8**	**69 ± 9**	**0.493**	**0.739**	**0.556**
Men	71 ± 11	69 ± 8	71 ± 8	/	/	/
Women	71 ± 13	68 ± 8	67 ± 8	/	/	/
BG (mmol/L)	**4.5 ± 0.4**	**4.6 ± 0.4**	**4.5 ± 0.5**	**0.584**	**0.108**	**0.493**
Men	4.6 ± 0.5	4.7 ± 0.5	4.7 ± 0.5	/	/	/
Women	4.4 ± 0.3	4.6 ± 0.4	4.3 ± 0.4	/	/	/

BMI = body mass index, BMR = basal metabolic rate, SBP = systolic blood pressure, DBP = diastolic blood pressure, LBM = lean body mass, PP = pulse pressure, BG = fasting blood glucose. $p \leq 0.05$.

p = 0.004; CI: 0.194 to 1.043). There was a significant main effect of time for lean body mass (F(2,34) = 4.290; p = 0.022; η_p2 = 0.201) between day 8 and day 15 (MD:0.477; p = 0.038; CI: 0.23 to 0.930). Moreover, significance was detected for the interaction between time and sex for lean body mass (F(2,34) = 1.134; p = 0.026; η_p2 = 0.194). Lastly, significance in lean body mass was also detected for sex (F(1,17) = 73.715; p < 0.001; MD = 16.212; CI: 12.228 to 20.196; d = 3.8). No other main or interaction effects were observed in the remaining physiological variables during the control period (Table 1). Regarding physical activity (Fig. 2) step count remained consistent during the control period (F(1,15) = 0.376; p = 0.549; MD = 227; CI: 564 to 1019; η_p2 = 0.024), with no sex (F(1,15) = 2.985; p = 0.105; MD = 1984; CI: 463 to 4432; d = 1.2) or interaction (F(2,34) = 0.407; p = 0.533; η_p2 = 0.026) effects being present.

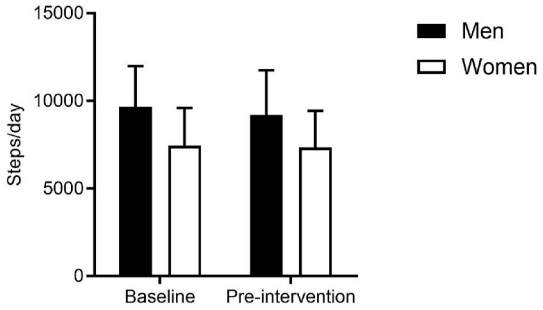

Fig. 2. Step count during control period (i.e. 1-7 days and 8–14 days).

3.2. Study period (Day 1–29)

Anthropometric and metabolic parameters (Table 2): There was a significant main effect of time on body mass (F(2,34) = 60.686; p < 0.001; η_p2 = 0.781) with a 3% body mass loss in both men and women. Significance was reached between control and day 22 (MD = 2.855; p < 0.001; CI:2.190 to 3.520), control and day 29 (MD = 1.681; p < 0.001; CI: 0.997 to 2.366), as well as between day 22 and day 29 (MD = −1.174; p = 0.001; CI: −1.897 to −0.450). There was a significant interaction between time and sex on body mass (F(2,34) = 7.368; p = 0.002; η_p2 = 0.302), however, no sex difference was detected ((F(1,17) = 3.646; MD = 10.725; CI: −1.125 to 22.575; p < 0.073; d = 0.87). For BMI, a significant main effect of time (F(2,34), p < 0.001, η_p2 = 0.827) was reached between day control and day 22 (MD = 0.992; CI: 0.818 to 1.167; p < 0.001), control and day 29 (MD = 0.562; CI: 0.333 to 0.792; p < 0.001) as well as between day 22 and day 29 (MD = −0.430; CI: −0.645 to −0.215; p < 0.001). Furthermore, an interaction effect between time and sex was present for BMI (F(2,34) = 7.684; p = 0.002; η_p2 = 0.827). Significance for time was also achieved for body fat (F(2,34) = 23.683; p < 0.001, η_p2 = 0.582). This significance was achieved between control and day 22 (MD = 1.204; CI: 0.750 to 1.658; p < 0.001), control and day 29 (MD = 1.111; p = 0.001; CI: 0.469 to 1.1754), but no significance was observed between day 22 and day 29 (MD: −0.093; p = 1.000; CI: −0.520 to 0.335). Moreover, significance on body fat % was achieved for the interaction between time and sex (F(2,34) = 3.460; p = 0.043; η_p2 = 0.169) and for main effect of sex on body fat % (MD = 11.386; p = 0.001; CI: 5.512 to 17.260; d = 1.9). A significant main effect of time was also observed for lean body mass (F(2,30) = 9.030; p = 0.001; η_p2 = 0.376) between control and day 22 of the study (MD = 1.030; p = 0.001; CI: 0.445 to 1.615) as well as between day 22 and day 29 of the study (MD = −0.665; p = 0.028; CI: −1.265 to −0.065). Additionally, a sex difference for lean body mass was detected (F(1,15) = 63.325; MD = 15.053; p < 0.001; CI: 11.021 to 19.068; d = 4.0), which is typical biological distinction between men and women (see Table 3).

Significant main effect of sex was achieved for BMR (MD = 366; p < 0.001; CI: 191.111 to 540.831, d = 1.6). A main effect of time was also observed for SBP (F(2,34) = 5.727; p = 0.007; η_p2 = 0.252), however, only between control and day 22 (MD = 8.835; p = 0.007; CI: 2.275). A significant effect of time was also detected for DBP (F(2,34) = 3.788; p = 0.033; η_p2 = 0.182), but only between control and day 29 of the study (MD = 4.780; p = 0.046; CI: 0.065 and 9.496). For pulse pressure, significant effect for interaction between time and sex was achieved (F(2,34) = 3.991; p = 0.028; η_p2 = 0.190).

Lastly, a significant main effect of time of blood glucose (F(2,34) = 11.755; p < 0.001; η_p2 = 0.409) was reached between control and day 22 (MD = 0.358; p = 0.002: CI: 0.129 to 0.587) and day 22 and day 29 (MD = −0.586; p = 0.001; CI: −0.0945 to −0.227). No other main or interaction effects were observed in the remaining variables during the

Table 2
Anthropometric, metabolic and physiological measures during entire study period.

	Control	Day 22	Day 29	Statistical significance of effect of:		
Variable	Mean ± SD	Mean ± SD	Mean ± SD	Time	Sex	Time x Sex
Body mass (kg)	**83.9 ± 13.4**	**81.0 ± 12.9**	**82.3 ± 12.6**	**<0.001***	**0.073**	**0.002***
Men	90.5 ± 14.0	87.4 ± 13.3	87.9 ± 13.6	/	/	/
Women	78.9 ± 11.2	76.4 ± 10.9	78.2 ± 10.6	/	/	/
BMI (kg/m2)	**29.7 ± 4.0**	**28.6 ± 3.8**	**29.1 ± 3.7**	**<0.001***	**0.873**	**0.002***
Men	29.6 ± 4.0	28.6 ± 4.0	28.7 ± 3.9	/	/	/
Women	29.7 ± 4.2	28.7 ± 4.0	29.4 ± 3.8	/	/	/
Body fat (%)	**33.4 ± 7.9**	**32.2 ± 8.3**	**32.3 ± 8.5**	**0.001***	**0.001***	**0.043**
Men	27.1 ± 5.7	25.6 ± 6.2	25.5 ± 6.7	/	/	/
Women	37.9 ± 5.9	37.0 ± 5.9	37.3 ± 5.8	/	/	/
LBM (kg)	**52.3 ± 8.8**	**51.3 ± 8.6**	**52.1 ± 8.2**	**0.001***	**<0.001***	**0.125**
Men	61.5 ± 5.8	60.3 ± 5.3	60.6 ± 5.1	/	/	/
Women	45.9 ± 2.3	45.1 ± 2.4	46.1 ± 2.5	/	/	/
BMR (kcal/24h)	**1465 ± 264**	**1403 ± 265**	**1499 ± 312**	**0.164**	**<0.001***	**0.828**
Men	1666 ± 263	1610 ± 206	1727 ± 259	/	/	/
Women	1318 ± 183	1252 ± 193	1334 ± 238	/	/	/
SBP (mm Hg)	**135 ± 17**	**126 ± 16**	**130 ± 14**	**0.007***	**0.086**	**0.737**
Men	142 ± 17	133 ± 19	135 ± 15	/	/	/
Women	129 ± 19	120 ± 11	126 ± 14	/	/	/
DBP (mm Hg)	**80 ± 11**	**75 ± 8**	**75 ± 10**	**0.033***	**0.225**	**0.183**
Men	82 ± 12	81 ± 10	76 ± 13	/	/	/
Women	79 ± 13	71 ± 5	74 ± 8	/	/	/
PP (mm Hg)	**69 ± 7**	**69 ± 9**	**66 ± 9.6**	**0.183**	**0.058**	**0.028***
Men	70 ± 9	73 ± 6	72 ± 5	/	/	/
Women	69 ± 10	67 ± 10	61 ± 9	/	/	/
BG (mmol/L)	**4.5 ± 0.3**	**4.1 ± 0.3**	**4.7 ± 0.6**	**<0.001***	**0.113**	**0.651**
Men	4.7 ± 0.5	4.3 ± 0.4	5.0 ± 0.7	/	/	/
Women	4.4 ± 0.4	4.2 ± 0.3	4.6 ± 0.6	/	/	/

BMI = body mass index, BMR = basal metabolic rate, SBP = systolic blood pressure, DBP = diastolic blood pressure, LBM = lean body mass, PP = pulse pressure, BG = fasting blood glucose. $p \leq 0.05$. Day 22 is the end of intervention period and day 29 is the end of the post-intervention period.

control period.

3.3. Measures of physical activity

Step count did not significantly change during the course of the study period ($F(2,34) = 1.089$; $p = 0.348$; $\eta_p2 = 0.060$). Moreover, no sex differences ($F(1,17) = 2.374$; $p = 0.142$; $d = 0.6$), or interaction between sex and time ($F(2,34) = 1.554$; $p = 0.226$; $\eta_p2 = 0.060$) were detected.

Similarly, PAEE did not reach significance for either time ($F(2,34) = 1.528$; $p = 0.231$; $\eta_p2 = 0.082$), sex ($F(1,17) = 1.771$; $p = 0.201$; $d = 0.6$), or their interaction ($F(2,34) = 0.396$; $p = 0.676$; $\eta_p2 = 0.023$).

Table 3
PA measures during entire study period.

	Pre-Intervention	Intervention	Follow-up	Statistical significance of effect of:		
Variable	Mean ± SD	Mean ± SD	Mean ± SD	Time	Sex	Time x Sex
Step count	**8212 ± 2411**	**7539 ± 2677**	**8246 ± 2985**	**0.348**	**0.142**	**0.226**
Men	9423 ± 2435	8824 ± 2330	8629 ± 3322	/	/	/
Women	7332 ± 2070	6605 ± 2611	7968 ± 2848	/	/	/
PAEE (kcal)	**387 ± 166**	**343 ± 192**	**370 ± 213**	**0.231**	**0.201**	**0.676**
Men	453 ± 196	418 ± 241	420 ± 279	/	/	/
Women	339 ± 129	289 ± 134	333 ± 154	/	/	/

PAEE = physical activity energy expenditure. $p \leq 0.05$.

3.4. Dietary compliance survey

Of the 19 participants who successfully finished the study, 14 completed the study compliance survey. The remaining 5 participants did not respond. The results showed that only one participant consumed and/or ingested energy dense foods or beverages, nicotine and/or alcohol prior to any of the 5 visits to the laboratory and two participants reported that they were not able to consume all the given liquid diet formula. Two other participants reported consumption of energy dense food and/or beverages, which were not part of the liquid diet.

4. Discussion

This study demonstrated that a 7-day diet-induced ER of 50% TDEE can reduce body mass and decrease fasting blood glucose levels and systolic blood pressure without eliciting detrimental changes in BMR, steps count and PAEE in both men and women.

Significant body mass losses were observed after 7 days of diet-induced ER in both men (−3.1 kg) and women (−2.5 kg). Moreover, after adjusting for total body mass, body mass losses were identical and accounted for 3% of total body mass in both groups. These findings are in line with previous studies investigating body mass change in response to a similar diet [5,6,31]. Interestingly, at follow-up (i.e. 7 days after ad-libitum energy intake resumed), body mass changes became more divergent between men and women. In men, body mass regain was only 0.5 kg whereas women experienced a threefold greater body mass regain, which amounted to 1.8 kg. Because PAEE and step count did not significantly differ between the two groups, a divergent response in post-starvation hyperphagia may explain the greater body mass gain observed in women [32]. Indeed, volitional body mass loss and its maintenance seem to result in augmented fasting and post-prandial appetite, which is mainly driven by alterations in hormonal regulators of appetite and can contribute to body mass gain [33]. [34] in a recent review suggested that although body mass loss results in increased fasting and post-prandial appetite, these changes do not seem to differ between men and women. Similar findings were reported in a short-term trial by Ref. [35] where no divergent responses in appetite regulation between men and women were found after a single day of 800 kcal ER. It is important to highlight, however, that [34] analysed only longer-term trials (3+ weeks of ER) whereas [35] investigated a single day of ER. This is important because compensatory responses to alterations in energy intake may start to manifest with a 3 to 4-day lag [36,37].

Although in the present study, there were no significant differences in PAEE and step count, both PAEE (−44 kcal) and step count (−673

steps) decreased during the diet-intervention period. Interestingly, after 7 days of ad-libitum energy intake, only women recovered PAEE (-6 kcal) and step count (+663 steps) to baseline values. By contrast, in men, PAEE (−33 kcal) and step count (−793 steps) did not return to baseline values but rather, reduction continued during the 7 days of ad-libitum energy intake. This divergent response between men and women in PAEE and step count during the post-intervention period may be partly explained by the different time period in which data collection was carried out; most of the female participants were recruited between February and May, whereas most male participants were recruited between May and July. Evidence suggests that seasonal variations in physical activity, self-weighing behaviour and body mass management may have served as an incentive in the men's group to maintain the body mass reduced state [38]. If seasonal variation played a key role in body mass change after the diet intervention, then analysis of BMR at follow-up (day 29) should have also shown a trend for decrease, however, that was not the case. Another possible explanation could be attributed to the protective role of a higher energy flux in men [39]. Mounting evidence suggests that coupling a high energy intake to a high energy expenditure can aid maintenance of a reduced body mass state by fine-tuning appetite at higher energy expenditures [40]. In the study, men had a consistently higher step count than women during control (+22%), diet-intervention (+25%) and post-intervention periods (+7%), which in turn might have resulted in a better appetite regulation after the diet-intervention [41].

Changes in BMR were assessed using indirect calorimetry before participants commenced the diet intervention (control period), immediately after the diet (day 22) and at follow-up (day 29). We observed a significant difference in BMR between men and women. Although BMR is determined by all metabolically active tissue, including the liver, brain and kidney, skeletal muscle has been shown to be main factors contributing to the metabolic discrepancy between men and women [41]. In fact, this divergence in BMR seems to further dissipate after BMR is adjusted in proportion to LBM only [9]. After the diet-induced ER (day 22), BMR decreased in both men and women by 56 kcal and 66 kcal, respectively. The observation that reductions in body mass led to a decrease in BMR has been extensively investigated [22]. Schwartz and Doucet (2008)reported that for every kg of body mass that is lost, BMR decreases by approximately 15 kcal, which largely explains the BMR drop observed in the study. This metabolic adaptation often persists after body mass loss, and in some cases can become permanent thus eliciting an energy gap [42]. The latter can be defined as the discrepancy between energy requirements and appetite following successful body mass loss, which in turn promotes body mass regain [9,42,43]. That said, manifestation of the energy gap is predominantly observed in longer-term studies where losses in body mass are more than 5% [44]. Interestingly, metabolic adaptations seem to be greater in magnitude during the first days of ER, mainly due to reduced insulin and leptin concentrations, intracellular water and glycogen content of skeletal muscle [31]. Nonetheless, BMR returned to baseline values after the final 7 days of ad-libitum energy intake (day 29), which is in line with the findings of previous studies, and therefore suggests a high degree of plasticity of BMR in response to changes in energy intake [43–45]. In addition to body mass, BMR, PAEE and step count, we measured changes in systolic blood pressure, diastolic blood pressure and fasting blood glucose, which all showed significant improvements with the diet-induced intervention. Positive changes in these markers of hypertension and insulin sensitivity are often reported in interventions where body mass loss is at least 3% of the initial body mass, which significantly reduces the risk of obesity-related diseases and mortality [46].

4.1. Study limitations

The conditions under which the indirect calorimeter was used included the use of the Weir's equation coupled with the dismissed protein oxidation and testing in a laboratory where strict temperature control was not possible, therefore this may have affected intra-individual variance BMR [23]. Furthermore, we did not control for changes in appetite, BMR and PAEE that may occur across different phases of the menstrual cycle and/or due to oral contraceptives [47] Moreover, our survey found that results might have been partially skewed by 5 participants who were not fully compliant with the study. However, this is an important finding and suggests the use of anonymous compliance surveys should become common practice in these types of studies. Due to some participants withdrawing from the study, the target number of participants was not reached. Therefore, the smaller sample size and uneven group sizes must also be considered when interpreting the findings of this study [48].

The main strengths of our study were the implementation of a control period, a diet-induced ER that was proportional to the individual's TDEE, objective assessment of PA and the frequent assessment of BMR via indirect calorimetry. This study therefore provided insights on how mild (3%) body mass loss can improve the measured health markers in both men and women. In practical applications, similar diet-induced ER can be potentially implemented over the short term in specific contexts where rapid body mass loss is paramount (i.e. pre-surgery body mass loss), and without conferring detrimental effects in BMR and LBM. In future research, we would like to emphasise the potential refinement of such studies by implementing doubly-labelled water to assess TDEE and four compartment models to asses body composition (e.g. DXA).

4.2. Conclusions

The present study demonstrates that 7 days of diet-induced ER at 50% TDEE can translate in favourable changes in body mass, body composition, blood fasting glucose, systolic blood pressure and diastolic blood pressure in overweight and obese adults. These rapid changes occurred concomitantly and in the absence of significant detrimental effects in BMR, PAEE and step count in both men and women. Findings suggest that men may also be more likely to maintain a state of reduced body mass than women. The implementation of anonymous compliance surveys is also recommended for future studies.

Authors statement

All authors declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. We confirm that the manuscript has been read and approved by all named authors and that the order of authors listed in the manuscript has been approved by all of us. We understand that the Corresponding Author is the sole contact for the Editorial process and therefore responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

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Ethical statement

This study obtained ethics approval from the School of Applied Health Sciences ethics committee of Abertay University and all participants provided written informed consent.

Declaration of competing interest

None.

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Appendices

Compliance survey

Q1 - Prior to assessments of basal metabolic rate, did you consume food/caffeine/nicotine?

A1 – Yes.
A2 – No.
A3 – I do not remember.

Q2 - If the answer to the previous question was YES, do you remember which study day was that? (Multiple choice)

A1 – Study day 1.
A2 – Study day 8.
A3 – Study day 15.
A4 – Study day 22.
A5 – Study day 29.
A6 – I do not remember.

Q3 - During the 7-day diet intervention, did you manage to finish all of your liquid diet?

A1 – Yes.
A2 – No.
A3 – I do not remember.

Q4 - During the 7-day diet phase of the study, did you consume any other caloric food/beverage outside of the liquid diet?

A1 – Yes.
A2 – No.
A3 – I do not remember.

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