**The effects of empagliflozin, dietary energy restriction, or both on appetite-regulatory gut peptides in individuals with type 2 diabetes and overweight or obesity: the SEESAW randomised, double-blind, placebo-controlled trial**

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**Short running title:** Empagliflozin, energy-restriction and appetite-regulatory peptides

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**Abstract word count:** 246

**Manuscript word count:** 3774

**Number of references:** 41

**Number of tables and figures:** 5 (2 tables, 3 figures)

**Keywords:** gut hormones, energy balance, SGLT2 inhibitors, energy restriction, compensation

**Structured Abstract**

***Aim:***To assess the impact of the SGLT2 inhibitor empagliflozin (25mg once-daily), dietary energy restriction, or both combined, on circulating appetite-regulatory peptides in people with type 2 diabetes (T2D) and overweight or obesity.

***Materials and Methods****:* In a double-blind, placebo-controlled trial, 68 adults (age 30-75 years) with T2D (drug naïve or on metformin monotherapy; HbA1c 6.0-10.0% [42-86mmol/mol]) and BMI ≥25kg/m2 were randomised to: (1) placebo-only, (2) placebo-plus-diet, (3) empagliflozin-only, or (4) empagliflozin-plus-diet for 24 weeks. Dietary energy restriction matched the estimated energy deficit elicited by SGLT2 inhibitor therapy through urinary glucose excretion (~360kcal/day). The primary outcome was change in postprandial circulating total peptide-YY (PYY) during a 3-hour mixed-meal tolerance test from baseline to 24-weeks. Postprandial total glucagon-like peptide-1 (GLP-1), acylated ghrelin and subjective appetite perceptions formed secondary outcomes, along with other key components of energy balance.

***Results****:* The mean weight loss in each group at 24 weeks was 0.44, 1.91, 2.22, and 5.74 kg, respectively. The change from baseline to 24 weeks in postprandial total PYY was similar between experimental groups and placebo-only (mean difference [95% CI]: -8.6: [-28.6 to 11.4], 13.4 [-6.1 to 33.0], and 1.0 [-18.0 to 19.9] pg/mL in placebo-plus-diet, empagliflozin-only, and empagliflozin-plus-diet groups, respectively (all *p*≥0.18)). Similarly, there was no consistent pattern of difference between groups for post-prandial total GLP-1, acylated ghrelin, and subjective appetite perceptions.

***Conclusions****:* In people with T2D and overweight or obesity, changes in postprandial appetite-regulatory gut peptides may not underpin the less-than-predicted weight loss observed with empagliflozin therapy.

**Clinical trials registration:** NCT02798744, www.ClinicalTrials.gov; 2015-001594-40, www.EudraCT.ema.europa.eu; ISRCTN82062639, www.ISRCTN.org.

**Introduction**

Sodium-glucose co-transporter 2 inhibitors (SGLT2i) are a class of glucose-lowering therapy in type 2 diabetes (T2D) that promote glucosuria,1 with the energy deficit resulting from increased urinary glucose excretion (~300-360kcal/day) underpinning their weight-lowering properties.2,3 However, the weight loss observed in both clinical trials and observational studies is 50-75% less than predicted based on modelling urinary glucose excretion alone.2

Reduced resting energy expenditure (EE) and increased appetite are well-established responses to weight loss in humans after diet or bariatric surgery,4 and evidence indicates that compensatory eating may play a key role in attenuating SGLT2i induced weight loss.5 Specifically, a modelling study in humans with T2D estimated that a 13% increase in energy intake (EI) partly explained a lower-than-predicted weight loss (~8kg) observed after 90 days of empagliflozin therapy.6 A similar analysis, following 52 weeks of canagliflozin therapy, suggested that EI increased by ~100kcal/day for each kilogram of weight loss achieved.7 An uncontrolled prospective study in humans (using data from a self-report food frequency questionnaire) support these analyses,8 along with preclinical evidence reporting a dose-dependent increase in EI after dapagliflozin administration in rats with diet-induced obesity.9 In the same rodent study, restricting food provision to that consumed by the placebo group augmented the weight loss elicited by dapagliflozin. The extent to which dietary energy restriction can potentiate the weight loss elicited by SGLT2i therapy in humans remains an important question.5

The regulation of EI in humans is complex and underpinned by homeostatic, hedonic and environmental factors.10 Within contemporary models of appetite control, a network of circulating peptides influence eating behaviour and energy homeostasis on an acute (meal-to-meal) and chronic basis.10 Specifically, peptide-YY (PYY) and glucagon-like peptide-1 (GLP-1) are gut-derived post-prandial satiety signals that facilitate efficient nutrient digestion and metabolism,11,12 whilst acylated ghrelin is an orexigenic peptide implicated in the cephalic phase of digestion and meal initiation.13,14 These acute signals are moderated by leptin and insulin which inform central appetite circuits about chronic energetic status.15,16 Reductions in circulating leptin and insulin are common responses to weight loss which may encourage compensatory eating 3,17,18, although this has recently been debated19. Data on the effects of SGLT2i therapies on appetite and appetite-regulatory peptides in humans are sparse, and limited to small and/or uncontrolled studies.20–22 Robust evidence from purposive randomised controlled trials is needed to better understand the effects of SGLT2i therapies on appetite and energy balance in individuals with T2D.

The primary aim of this study was to investigate the effects of 24 weeks of empagliflozin therapy, an energy-restricted diet, or both combined, on appetite-regulatory gut peptides in adults with T2D and overweight or obesity, compared to placebo. Effects on subjective appetite perceptions, insulin and leptin, and other components of energy balance comprised key secondary aims. We hypothesised that empagliflozin would result in an altered profile of appetite-regulatory peptides commensurate with increased perceived appetite (lower total PYY, GLP-1, and higher acylated ghrelin). Moreover, these responses would be greater when combined with an energy-restricted diet, in accordance with greater weight loss.

**Materials and Methods**

*Study design and participants*

SEESAW was a 24-week, randomised, double-blind, placebo-controlled, phase 4 trial conducted at a single clinical research site in Leicester, UK. The trial protocol received full ethical approval from an NHS Research Ethics Committee (16/EM/0040), with all participants giving written, informed consent to participate.

Eligible participants were men or post-menopausal women, aged 30-75 years, with BMI ≥25kg/m2 and T2Dcontrolled through lifestyle advice alone or stable metformin monotherapy (HbA1c 6⋅0-10⋅0% [42-86mmol/mol]). Key exclusion criteria included individuals with type 1 diabetes, eGFR <60mL/minper 1⋅73m2, familial glucosuria, or other contraindications to SGLT2i therapy. Those prescribed loop diuretics and those consuming a severely energy-restricted diet (<800kcal/day) were also excluded. Pre-menopausal women were excluded given that menstrual cycle phase impacts appetite control and eating behaviour, making standardisation problematic23. A full list of eligibility criteria is provided in supplementary methods.

Participants were randomised (1:1:1:1) using an independent online computerised randomisation system (Sealed Envelope Ltd, London, UK), to one of four groups: (a) placebo-only, (b) placebo plus energy-restricted diet (“placebo-plus-diet”), (c) empagliflozin 25mg only (“empagliflozin-only”), or (d) empagliflozin 25mg plus energy-restricted diet (“empagliflozin-plus-diet”). Randomisation was stratified by age (≤/>50 years) and BMI (</≥30kg/m2) and occurred after all baseline measurements.

*Procedures*

Empagliflozin 25mg or matched placebo were taken orally once daily. Participants unable to tolerate 25mg of empagliflozin or placebo therapy were withdrawn.

Participants randomised to placebo-plus-diet or empagliflozin-plus-diet groups underwent a personalised energy-restricted diet designed to reduce EI by 360kcal/day; approximately matching the estimated energy deficit elicited by SGLT2i therapy.3,24 Participants received support to identify and maintain a personalised approach to reach a daily EI target, based upon their estimated daily energy requirements (assessed using indirect calorimetry), and accounting for self-reported physical activity. Targets were revised after 6 and 12 weeks.

Participants attended five experimental visits (Visits 1-5), occurring at baseline, 2, 6, 12 and 24 weeks. Dietary intake (including alcohol and caffeine) and structured physical activity were standardised before each visit. Upon arrival (08:00-09:00h), body mass, BMI, body fat percentage, waist circumference, hip circumference, resting blood pressure and heart rate, and resting EE (indirect calorimetry; GEM open-circuit ventilated hood system, GEM Nutrition Ltd., Cheshire, UK) were measured using standardised procedures.

Approximately 90min into Visits 1-5, participants underwent a 3-hour mixed meal tolerance test (MMTT). An intravenous cannula was inserted into an antecubital or forearm vein, after which participants rested for 30min to ensure habituation.25 A fasted blood sample was then collected, before participants consumed a standardised breakfast meal within 15min. Each participant consumed the same meal at each of their visits, containing ~33% of their baseline estimated daily energy requirements and comprising approximately 50% carbohydrate, 15% fat and 35% protein. Further blood samples were collected 30, 60, 90, 120, 150 and 180min after the final mouthful. Subjective appetite perceptions (hunger, fullness, satisfaction and prospective food consumption) were assessed using 100mm visual analogue scales (VAS) immediately before sample collection.26

Blood samples were drawn into chilled tubes pre-treated with an anticoagulant or clotting factor, for the isolation of plasma or serum, respectively. To prevent degradation of acylated ghrelin, one tube was treated with a protease inhibitor cocktail according to manufacturer instructions. Clinical biomarkers were measured using standardised quality-controlled assays within local pathology laboratories. Remaining samples were spun immediately in a refrigerated centrifuge, before plasma/serum were isolated and stored at -80ºC for future batch analysis of total PYY, total GLP-1, acylated ghrelin, leptin (all ELISA), insulin, glucagon, and c-peptide (multiplex assay). Further details, including assay manufacturer details and co-efficients of variation, are included in supplementary methods.

Participants completed the three-factor eating questionnaire (TFEQ)27 and the international physical activity questionnaire (IPAQ; long last 7 days format) at each experimental visit, to assess cognitive dietary restraint, disinhibition and hunger, and self-reported physical activity, respectively. Body composition was assessed at Visits 1 and 5 only, using dual-energy X-ray absorptiometry (DEXA; Lunar Prodigy, GE Corporation, Connecticut, USA). Accelerometer-assessed physical activity volume and intensity were captured after Visits 0, 3, 4 and 5 (wGT3X-BT, Actigraph, Pensacola, FL, USA). Self-reported daily EI was measured prior to Visits 0 and 5 using food diaries.

*Outcomes*

The primary outcome was change from baseline to 24 weeks in postprandial circulating total PYY response during the MMTT. This was assessed via time-averaged total AUC, calculated using the trapezoid method and divided by 3h (see supplementary methods for further details). Time-averaged AUC values represent the average concentration across the postprandial period.28,29

Secondary outcomes were change in postprandial total PYY response at 2, 6 and 12 weeks, and change in the following outcomes at 2, 6, 12 and 24 weeks: postprandial responses of total GLP-1, acylated ghrelin, subjective appetite perceptions, glucose, insulin, C-peptide and glucagon; fasting concentrations of leptin (absolute and normalised to body weight), glucose and insulin; TFEQ dimensions; HbA1c; body weight; DEXA-derived body composition (24 weeks only); total body fat percentage (bioelectrical impedance analysis); waist and hip circumferences; daily EI (24 weeks only); resting EE; accelerometer-assessed (6, 12 and 24 weeks only) and self-report (IPAQ) physical activity and sedentary behaviour; CRP; fasting lipids; eGFR; alanine aminotransferase (ALT); and resting blood pressure and heart rate.

Change in all of the above across the follow-up period collectively (analysed using generalised estimating equations; see below) also comprised secondary outcomes.

*Sample size*

We required 15 participants per group to complete all trial procedures, to detect a 120pg/mL difference in postprandial total PYY between experimental groups and placebo-only with 80% power, assuming a SD of 96⋅2pg/mL and a two-sided alpha error rate of 1⋅7% (*p*<0⋅017).30 The latter allowed three comparisons (one for each experimental group) against placebo-only.

*Statistical analysis*

The primary analysis compared change from baseline in postprandial total PYY at 24 weeks in each experimental group versus placebo-only, using a generalised linear model (GLM) adjusted for age, BMI and baseline total PYY response, utilising a complete cases approach. Two sensitivity analyses of the primary outcome were performed, repeating the primary analysis in both “intention-to-treat” (ITT) and “per protocol” populations (see supplementary methods for details).

Secondary outcomes were analysed using GLM as outlined above at 2, 6, 12, and/or 24 weeks (as appropriate), with analyses of accelerometer-measured outcomes additionally adjusted for device wear time. Generalised estimating equations (GEE) were performed for each outcome to complement GLM analyses at each timepoint. GEE accounts for repeated measurements, does not require imputation or exclusion of participants for missing data, and can be interpreted as a ‘summary’ intervention effect across the entire follow-up period. GEE analyses compared each experimental group with placebo-only, using a normal distribution and an exchangeable correlation matrix, and were adjusted as per GLM models. Statistical analyses were performed using STATA v16.1 (StataCorp LP, Texas, USA).

Comparisons between experimental groups and placebo-only are reported as adjusted mean difference (experimental group minus placebo-only) with 95% CI. To account for multiple testing, statistical significance of all comparisons was determined using Holm’s sequential Bonferroni procedure, whereby the three *p*-values for comparisons within a given analysis were assessed sequentially, from lowest to highest, against thresholds of 0⋅017, 0⋅025 and 0⋅050, respectively, stopping once a *p*-value was greater than the threshold to which it was being compared. Further details of statistical analyses can be found in supplementary methods.

**Results**

*Participant flow and baseline characteristics*

Participant flow is outlined in Figure 1. Recruitment took place between 4th January 2017 and 16th January 2019. Of 68 randomised participants, 63 completed the trial. Within-group change and between-group analyses for all trial outcomes are provided in Tables S2-S4. Those related to appetite regulation, energy balance and glycaemic control are presented in detail below.

Baseline participant characteristics for each group are presented in Table 1 (see Table S1 for combined population). Participants had a median age of 63 years, diabetes duration of 6 years, HbA1c of 6.9% (52mmol/mol) and BMI of 31.8kg/m2.Thirty-five percent were female, and 82% were receiving metformin monotherapy for the management of their diabetes. Characteristics were similar across groups, except that there was a greater proportion of female participants in the groups receiving empagliflozin, a lower proportion of individuals receiving metformin monotherapy in the groups receiving the energy-restricted diet, and median diabetes duration was 2-3 years shorter in the placebo-plus-diet group.

*Body weight changes*

The mean weight loss from baseline to 24 weeks was 0.44, 1.91, 2.22 and 5.74 kg in placebo-only, placebo-plus-diet, empagliflozin-only and empagliflozin-plus-diet groups, respectively. Compared to placebo-only, body weight was lower across individual timepoints and follow-up collectively in both of the empagliflozin groups, except in the empagliflozin-only group at 24 weeks (which did not reach statistical significance after correction for multiple comparisons). In the placebo-plus-diet group, body weight was statistically lower than placebo-only at 6 weeks (Figure 3A, Tables 2 and S3).

*Appetite-regulatory peptides*

Primary outcome data at baseline and 24 weeks were available for 61 participants, who thus comprised the complete cases population for the primary analysis (Figure 1). There were no differences in postprandial total PYY at 24 weeks between experimental groups and placebo-only (Figure 2A, Table 2). Postprandial total PYY was higher at 12 weeks in the empagliflozin-only group, compared to placebo-only, but was otherwise similar between groups at 2, 6 and 12 weeks and across the follow-up period collectively. Results in the ITT population were similar to the primary analysis. However, in the per protocol analysis (placebo-only *n*=11, placebo-plus-diet *n*=8, empagliflozin-only *n*=12, empagliflozin-plus-diet *n*=13), postprandial total PYY was higher at 24 weeks in the empagliflozin-only group, compared to placebo-only (Figure 2A, Tables 2 and S2).

There were no differences in postprandial total GLP-1 or acylated ghrelin between experimental groups and placebo-only at 24 weeks or any intermediate timepoint (Figures 2B-C, Tables 2 and S2). However, across follow-up collectively, postprandial total GLP-1 was higher in the empagliflozin-only group. Fasting leptin was no different between experimental groups and placebo-only at 24 weeks and intermediate timepoints but was lower across follow-up collectively in the empagliflozin-plus-diet group (Figure 2D, Tables 2 and S2). This difference was attenuated and no longer statistically significant when leptin concentrations were normalised to body weight.

*Subjective appetite perceptions and self-reported energy intake*

There were no differences in VAS-derived appetite perceptions, TFEQ-measured disinhibition and hunger, or self-reported daily EI between experimental groups and placebo-only at any timepoint or across follow-up collectively (Figures S1A-D, Tables 2 and S2). However, cognitive dietary restraint was higher in the placebo-plus-diet and empagliflozin-plus-diet groups (significantly different in the empagliflozin-plus-diet group at 24 weeks and in both groups at 12 weeks and across follow-up collectively; Tables 2 and S2).

*Body composition and energy expenditure*

At 24 weeks, DEXA-derived total body fat mass was lower in the empagliflozin-plus-diet group, compared to placebo-only, whilst total lean body mass was lower in both the empagliflozin-only and empagliflozin-plus-diet groups (Tables 2 and S3). Resting EE was lower at 24 weeks in the empagliflozin-plus-diet group, compared to placebo-only (Figure 3B), but daily steps (Figure 3C), sedentary time, and light- and moderate-to-vigorous-intensity physical activity were similar in each experimental group versus placebo-only in all analyses (Tables 2 and S3).

*Glycaemic control*

Compared to placebo-only, HbA1c was lower at 24 weeks in the empagliflozin-plus-diet group, and lower in both empagliflozin-only and empagliflozin-plus-diet groups at 6, 12 weeks and across follow-up collectively (Figure 3D, Tables 2 and S4). It was lower in the placebo-plus-diet group at 2 and 6 weeks only. Fasted and post-prandial glucose concentrations were lower accordingly (see Tables 2 and S4 for details). Fasting plasma insulin was similar between experimental groups and placebo-only in all analyses performed, but postprandial insulin responses were lower at 24 weeks in all three experimental groups, as well as across follow-up collectively in the empagliflozin-only group (Tables 2 and S4). Postprandial glucagon responses were similar between experimental groups in all analyses.

*Adverse events*

Adverse event data are provided in Table S5. The total number of adverse events and the number of participants with at least one adverse event were similar between groups. Two serious adverse events occurred during the trial (one in each of the placebo-only and placebo-plus-diet groups), but neither were considered related to trial/intervention procedures and neither were fatal.

**Discussion**

The SEESAW trial investigated the effects of empagliflozin therapy, an energy-restricted diet, and their combination, on appetite regulation and key components of energy balance in people with T2D and overweight or obesity. Empagliflozin therapy and matched dietary energy restriction both induced weight loss but did not affect appetite regulatory hormones, appetite perceptions, habitual EI or EE. The combination of interventions potentiated weight loss, alongside reduced circulating leptin concentrations and resting EE, but appetite-regulatory gut peptides, appetite perceptions and EI remained unaffected. Glycaemic control was improved in both groups receiving empagliflozin therapy.

Evidence from murine experiments and human clinical trials indicates that the weight loss elicited by SGLT2i therapies is less than that predicted based on urinary glucose excretion.6,7,9 It has been suggested that increased EI, underpinned by enhanced appetite, contributes to this discrepancy,6–9 but this has not been comprehensively tested.5 The principal objective of the SEESAW trial was to examine the impact of our interventions on the appetite-regulatory peptides PYY, GLP-1 and acylated ghrelin. PYY is a gut peptide released into the circulation after meal ingestion that promotes satiety.12 PYY is released from L-cells predominantly within the lower intestine,31 along with GLP-1, another central acting satiety-related peptide that also modulates glycemia.32 Conversely, acylated ghrelin is a stomach-derived orexigenic peptide implicated in meal-initiation and energy conservation.33 Previous studies have described compensatory changes in the circulating levels of these peptides after weight loss, where PYY and GLP-1 are reduced, and acylated ghrelin is increased.4,34 Consequently, we hypothesised that empagliflozin and diet-induced weight loss would alter the profile of these peptides commensurate with increased hunger and reduced satiety, with such responses potentiated when the two interventions were combined.

In contrast to our hypothesis, postprandial total PYY was unaffected in our primary analysis (at 24 weeks), and in fact greater in the empagliflozin-only group within two of our secondary analyses (including our per protocol sensitivity analysis). Similarly, there were no differences between experimental groups and placebo-only in total GLP-1 at 24 weeks, but an increase in the empagliflozin-only group across follow-up collectively. Acylated ghrelin responses were not influenced by any of our interventions. Collectively, these findings indicate that empagliflozin therapy, matched weight loss through dietary energy restriction, and the combination of both do not provoke changes in circulating appetite-related peptides which would be expected to increase hunger and/or reduce satiety, in individuals with T2D and overweight or obesity. It is notable, however, that the magnitude of weight loss elicited in our study is less than that of previous trials within which compensatory responses (increased circulating ghrelin; reduced PYY, and GLP-1) to diet-induced weight loss have been observed.34 Therefore, changes in these peptides may only become apparent with interventions eliciting greater weight loss. Furthermore, circulating levels of PYY and GLP-1 are reduced in obesity,32,35 and thus the capacity for further reduction may be limited. Our documented increase in postprandial GLP-1 concentration in the empagliflozin and empagliflozin-plus-diet treated groups is interesting and may represent a partial normalisation of GLP-1 response secondary to weight loss19.

Working in synergy with acute appetite-regulatory peptides, leptin and insulin are chronic ‘adiposity signals’, which inform the brain about the repleteness of peripheral energy stores.10 Reductions in circulating leptin and insulin are well characterised responses to weight loss,36 which provoke energy conservation via central effects.37 Across our study, circulating leptin concentrations were reduced in the empagliflozin-plus-diet group, but were unchanged with diet or empagliflozin alone. Despite no change in any experimental group compared to placebo-only at 24 weeks, circulating leptin concentrations were reduced in the empagliflozin-plus-diet group across follow-up collectively. Whilst fasting insulin concentrations remained unchanged, insulin responses to the MMTT were reduced at 24 weeks in the empagliflozin-only and empagliflozin-plus-diet groups. Our data are consistent with a recent meta-analysis demonstrating reduced circulating leptin concentrations in people with T2D following therapy with another SGLT2i (ipragliflozin),18 whilst reductions in circulating insulin in response to SGLT2i therapy (including empagliflozin) have previously been documented in mechanistic experiments.3,17,24 Reductions in postprandial insulinemia in the empagliflozin groups likely occurred secondary to improvements in glycemia,17 whereas the greater weight (fat mass) loss, likely explains why leptin was reduced only in the empagliflozin-plus-diet group. The superior weight loss with the combination of interventions may also explain why resting EE was lower only in the empagliflozin-plus-diet group.

Another notable finding of our study is that subjective appetite perceptions were also unresponsive to each of the interventions. This suggests that the energy deficits elicited by empagliflozin therapy, dietary energy restriction, and their combination, did not provoke physiological responses reaching the level of consciousness in our participants. This finding contrasts previous data demonstrating increased subjective appetite (particularly an increase in fasting and meal-related hunger) in response to negative energy balance and weight loss,36 including a single, uncontrolled human study in individuals with T2D undergoing ipragliflozin therapy.22 These discrepant findings may be explained by the modest magnitude of weight loss elicited in our study (particularly in the placebo-plus-diet and empagliflozin-only groups; ~3 to 3⋅5% from baseline), or it may be that, despite exhibiting best practice, our assessment of appetite within a laboratory environment lacked sufficient sensitivity to detect subtle changes in subjective perceptions. It is also noteworthy that we observed no increase in self-reported EI in any experimental group compared to placebo. These findings contrast evidence from pre-clinical studies in rodents and previous modelling analyses in humans,6,8,9 but are in accordance with preliminary analyses from a randomised placebo-controlled crossover trial in people with T2D, which reports no change in laboratory-assessed food intake following 12 weeks of dapagliflozin therapy.38,39

This study was the first to assess the impact of SGLT2i therapy on habitual physical activity, which is the most variable component of total daily EE. Whilst our results do not suggest a conclusive effect (no statistically significant differences were apparent after adjustment for multiple comparisons), the nominally lower number of steps per day across follow-up in the empagliflozin-only group (~800 steps) is noteworthy and supportive data in rodents exist. In a study of mice undergoing canagliflozin therapy alongside a high-fat diet, daily wheel running was reduced compared to those fed high-fat diet alone.40 Potential changes in habitual physical activity after initiating SGLT2i therapy thus requires further investigation, particularly given the low habitual activity in our study population (~5000 steps/day), and that as little as 500 steps/day change in activity has been postulated as clinically meaningful.41

Key strengths of this trial include the precision in matching within-group weight change in the placebo-plus-diet and empagliflozin-only groups (-3.6 and -3.2%, respectively), as well as the detailed assessment of appetite regulatory responses to a MMTT and components of EE in a multi-ethnic population (~28% non-white). Lack of assessment of hedonic mediators of appetite control are a noteworthy limitation that should be investigated in future trials. Larger trials are also needed to examine whether the findings from our tightly controlled experimental design translate into changes in eating behaviour in real-world settings. The possibility that we may have been underpowered to detect small but potentially significant differences in some secondary outcomes should also be acknowledged.

In conclusion, this trial demonstrates that 24 weeks of empagliflozin therapy, matched diet-induced weight loss, or the combination of both, do not provoke consistent changes in appetite regulatory gut peptides (PYY, GLP-1 and acylated ghrelin) or subjective appetite perceptions in individuals with T2D and overweight or obesity. Therefore, changes in these outcomes, at least over 24 weeks, do not underpin potential compensatory increases in energy intake that have been suggested to attenuate the weight loss elicited with SGLT2i therapy. Future studies should scrutinise the impact of SGLT2i therapies on eating behaviour and its determinants, including hedonic mediators of appetite control, physical activity and exercise habits, as well as examine the combination of dietary interventions and SGLT2i in real-world clinical practice.

**Acknowledgements**

We would like to thank the participants for volunteering their time to participate in this study. We also thank all staff who supported aspects of trial set-up, management and delivery, particularly Natasha Wileman (Senior Trials Manager, Leicester Diabetes Centre, University Hospitals of Leicester NHS Trust).

**Funding**

This research was funded by an investigator-initiated grant from Boehringer-Ingelheim. The funder had no role in collection, analysis or interpretation of data, nor writing of the manuscript. They commented on initial trial design and reviewed the manuscript, but final decisions were made by the investigator team. This study was supported by the National Institute for Health Research (NIHR) Leicester Biomedical Research Centre and the NIHR Applied Research Collaboration East Midlands. The views expressed are those of the authors and not necessarily those of the NHS, the NIHR or the Department of Health and Social Care.

**Data availability**

The datasets generated during the current study are available from the corresponding author on reasonable request.

**Authors’ relationships and activities**

JAS and TY report funding in the form of an investigator-initiated trial from AstraZeneca.

DRW has received honoraria as a speaker for AstraZeneca, Sanofi-Aventis and Lilly, and has received research funding support from Novo Nordisk.

JPHW reports receiving consultancy fees (paid to University of Liverpool) in relation to obesity and type 2 diabetes in the last 12 months from AstraZeneca, Boehringer Ingelheim, Janssen Pharmaceuticals, Lilly, Mundipharma, Napp, Novo Nordisk, Rhythm Pharmaceuticals, Sanofi and Saniona; personal fees honoraria/lecture fees from AstraZeneca, Boehringer Ingelheim, Lilly, Napp, Mundipharma, Sanofi and Takeda; and research grant funding (via University of Liverpool) from AstraZeneca and Novo Nordisk.

KK has acted as consultant, advisory board member and speaker for Abbott, Amgen, Astrazeneca, Bayer, NAPP, Lilly, Merck Sharp and Dohme, Novartis, Novo Nordisk, Roche, Berlin-Chemie AG/Menarini Group, Sanofi-Aventis, Servier, Boehringer Ingelheim, EACME grants from Boehringer Ingelheim, AstraZeneca, Novartis, Novo Nordisk, Sanofi-Aventis, Lilly, Merck Sharp & Dohme.

MJD has acted as consultant, advisory board member and speaker for Novo Nordisk, Sanofi, Lilly and Boehringer Ingelheim, an advisory board member and speaker for AstraZeneca, an advisory board member for Janssen, Lexicon, Servier and Gilead Sciences Ltd and as a speaker for Napp Pharmaceuticals, Mitsubishi Tanabe Pharma Corporation and Takeda Pharmaceuticals International Inc. She has received grants in support of investigator and investigator initiated trials from Novo Nordisk, Sanofi-Aventis, Lilly, Boehringer Ingelheim, AstraZeneca and Janssen.

JAK, ELR, DHB, SC, CLE, LJG, BP, GW, HLW, SAW & DJS have no conflicts of interest to declare.

**Contribution statement**

MJD and SC generated the research idea. MJD, JK, TY, ELR, DB, SC, CLE, LJG, DRW, KK, & DJS designed the study and/or the statistical analysis plan. JAS, JAK, TY, ELR, SC, DRW oversaw data collection and/or intervention delivery. JAS, JAK, BP, HLW, SAW & DJS were responsible for biochemical analyses. CLE processed the accelerometer data. JAS, TY, DB, LJG & GW were responsible for data analyses. JAS, JAK, TY and MJD interpreted findings and drafted the manuscript. All authors commented on the draft, providing clinical and/or academic input, approved the final version and agree to be accountable for the work. JAS is the guarantor of the work and as such had full access to all the data and takes responsibility for the integrity of the data and the accuracy of the data analysis.

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**Figure legends**

**Figure 1 – Study consort diagram**

**Figure 2 – Difference between experimental groups and placebo-only at each timepoint (open symbols) and across follow-up (filled symbols) in appetite-regulatory gut peptides: (A) postprandial total PYY, (B) postprandial acylated ghrelin, (C) postprandial total GLP-1, and (D) fasting leptin.** Data are presented as adjusted mean difference (experimental group minus placebo-only) with 95% CI. Postprandial responses were assessed as time-averaged area under the concentration-time curve during the standardised 3-hour mixed meal tolerance test. All analyses were adjusted for age, BMI (both categorised as per randomisation) and baseline value of the outcome. \* Denotes comparison with placebo-only group was statistically significant after application of Holm’s sequential Bonferroni procedure to account for multiple comparisons. GEE analyses across follow-up can be inferred as the summary intervention effect. Abbreviations: GEE, generalised estimating equations; GLP-1, glucagon-like peptide-1; PYY, peptide YY.

**Figure 3 – Difference between experimental groups and placebo-only at each timepoint (open symbols) and across follow-up (filled symbols) in (A) total body weight, (B) resting energy expenditure, (C) daily steps, and (D) HbA1c.** Data are presented as adjusted mean difference (experimental group minus placebo-only) with 95% CI. All analyses were adjusted for age, BMI (both categorised as per randomisation) and baseline value of the outcome, with analyses of daily steps additionally adjusted for accelerometer wear time. \* Denotes comparison with placebo-only group was statistically significant after application of Holm’s sequential Bonferroni procedure to account for multiple comparisons. GEE analyses across follow-up can be inferred as the summary intervention effect. #statistical analyses of HbA1c were performed on data in mmol/mol only. Converted values of within-group change and between-group differences in % can be found in Supplementary Table 4. Abbreviations: GEE, generalised estimating equations; GLP-1, glucagon-like peptide-1; PYY, peptide YY.

**Tables**

**Table 1 – Participant characteristics at baseline in each group**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  |  | **Placebo only (n=17)** | **Placebo + Diet  (n=17)** | **Empagliflozin only (n=17)** | **Empagliflozin + Diet (n=17)** |
| Sex | Male | 13 (76.5) | 13 (76.5) | 8 (47.1) | 10 (58.8) |
|  | Female | 4 (23.5) | 4 (23.5) | 9 (52.9) | 7 (41.2) |
| Ethnicity | White European | 12 (70.6) | 13 (76.5) | 12 (70.6) | 12 (70.6) |
|  | South Asian | 3 (17.7) | 3 (17.7) | 3 (17.7) | 4 (23.5) |
|  | Other | 2 (11.8) | 1 (5.9) | 2 (11.8) | 1 (5.9) |
| Age (years) |  | 63 (56 – 69) | 63 (60 – 69) | 61 (57 – 68) | 65 (55 – 69) |
| Duration of diabetes (years) |  | 7.0 (6.5 – 8.0) | 4.0 (3.0 – 8.5) | 6.0 (2.5 – 11.0) | 6.5 (4.3 – 12.3) |
| Diabetes management | Lifestyle advice only | 1 (5.9) | 4 (23.5) | 2 (11.8) | 5 (29.4) |
|  | Lifestyle advice plus metformin monotherapy | 16 (94.1) | 13 (76.5) | 15 (88.2) | 12 (70.6) |
| *Glycaemic control* |  |  |  |  |  |
| HbA1c | % | 7.0 (6.6 – 7.4) | 6.9 (6.5 – 7.4) | 6.9 (6.5 – 7.1) | 6.8 (6.5 – 7.0) |
|  | mmol/mol | 53 (49 – 57) | 52 (48 – 57) | 51 (48 – 54) | 51 (48 – 53) |
| Fasting plasma glucose (mmol/L) |  | 6.9 (6.0 – 8.3) | 6.9 (5.7 – 7.5) | 6.4 (5.7 – 7.1) | 6.8 (5.9 – 7.3) |
| Fasting plasma insulin (mU/L) |  | 16.5 (10.2 – 21.5) | 13.2 (10.2 – 23.3) | 17.0 (11.3 – 23.8) | 12.7 (8.6 – 16.2) |
| Fasting plasma glucagon (pg/mL) |  | 62 (49 – 103) | 54 (39 – 84) | 58 (33 – 92) | 44 (35 – 76) |
| Fasting plasma C-peptide (pg/mL) |  | 1750 (1636 – 2248) | 1689 (1262 – 2471) | 1668 (1279 – 2437) | 1442 (840 – 1676) |
| *Anthropometry and body composition* |  |  |  |  |  |
| Body weight (kg) |  | 98.8 (86.9 – 107.4) | 96.9 (77.9 – 110.0) | 89.8 (75.7 – 96.2) | 90.3 (77.8 – 102.9) |
| BMI (kg/m2) |  | 32.8 (30.0 – 36.2) | 31.9 (28.4 – 36.8) | 31.4 (29.6 – 34.9) | 31.2 (28.8 – 34.3) |
| Body fat percentage (%) |  | 32.0 (30.0 – 36.5) | 34.5 (29.0 – 38.0) | 39.0 (29.5 – 42.5) | 32.0 (27.5 – 42.5) |
| Total fat mass (kg) |  | 36.3 (29.6 – 44.6) | 37.9 (25.6 – 42.8) | 33.5 (28.9 – 38.2) | 32.4 (28.4 – 39.3) |
| Total lean body mass (kg) |  | 56.4 (51.3 – 62.8) | 57.4 (46.4 – 66.3) | 46.0 (39.5 – 61.6) | 53.8 (44.3 – 58.2) |
| Total bone mass (kg) |  | 3.24 (2.55 – 3.48) | 3.15 (2.50 – 3.50) | 2.41 (2.16 – 3.29) | 2.79 (2.40 – 3.24) |
| Total bone mineral density (g/cm2) |  | 1.27 (1.21 – 1.37) | 1.24 (1.11 – 1.36) | 1.22 (1.09 – 1.31) | 1.19 (1.13 – 1.31) |
| Waist circumference (cm) |  | 113.0 (103.4 – 118.5) | 112.8 (97.0 – 120.5) | 110.0 (101.8 – 116.8) | 108.0 (98.0 – 117.2) |
| Hip circumference (cm) |  | 110.0 (104.0 – 118.5) | 109.8 (101.4 – 117.3) | 111.0 (104.5 – 117.0) | 108.6 (102.6 – 119.5) |
| *Energy balance and habitual physical activity* |  |  |  |  |  |
| Daily energy intake (kcal/day) |  | 1769 (1573 – 2170) | 1674 (1249 – 1897) | 1698 (1335 – 2139) | 1513 (1177 – 1742) |
| Resting energy expenditure (kcal/day) |  | 1566 (1213 – 1854) | 1486 (1282 – 1930) | 1466 (1152 – 1568) | 1431 (1302 – 1623) |
| Steps (number/day) |  | 5126 (3640 – 7198) | 4747 (3611 – 7261) | 5077 (4494 – 7912) | 5170 (3769 – 8533) |
| Sedentary time (min/day) |  | 611 (524 – 650) | 581 (556 – 658) | 567 (500 – 689) | 585 (519 – 641) |
| Light-intensity physical activity (min/day) |  | 268 (210 – 333) | 237 (186 – 290) | 308 (240 – 339) | 281 (231 – 317) |
| Moderate-to-vigorous-intensity physical activity (min/day) |  | 17 (10 – 37) | 16 (8 – 37) | 15 (11 – 25) | 19 (5 – 46) |
| *Renal and hepatic function* |  |  |  |  |  |
| eGFR (mL/min per 1.73m2) |  | 90 (83 – 90) | 90 (85 – 90) | 90 (88 – 90) | 90 (87 – 90) |
| Albumin (g/L) |  | 46 (43 – 48) | 45 (44 – 48) | 46 (44 – 47) | 46 (44 – 47) |
| Alkaline phosphatase (U/L) |  | 82 (75 – 94) | 66 (58 – 83) | 76 (65 – 92) | 85 (74 – 106) |
| Alanine transaminase (U/L) |  | 26 (20 – 36) | 35 (19 – 47) | 32 (20 – 54) | 27 (20 – 36) |
| Bilirubin (µmol/L) |  | 9 (8 – 10) | 10 (7 – 13) | 10 (8 – 10) | 7 (6 – 10) |
| *Blood pressure, lipids and other cardiometabolic risk factors* |  |  |  |  |  |
| Systolic blood pressure (mmHg) |  | 123 (112 – 134) | 130 (115 – 137) | 124 (116 – 132) | 116 (111 – 135) |
| Diastolic blood pressure (mmHg) |  | 75 (67 – 78) | 73 (69 – 85) | 73 (69 – 80) | 74 (67 – 78) |
| Resting heart rate (beats/min) |  | 74 (58 – 81) | 73 (69 – 79) | 71 (64 – 83) | 74 (67 – 85) |
| Total cholesterol (mmol/L) |  | 3.6 (3.2 – 4.3) | 4.0 (3.4 – 4.6) | 3.8 (3.4 – 4.6) | 4.0 (3.2 – 5.0) |
| HDL (mmol/L) |  | 1.1 (0.9 – 1.2) | 1.2 (1.0 – 1.4) | 1.4 (1.2 – 1.6) | 1.2 (1.0 – 1.3) |
| LDL (mmol/L) |  | 1.7 (1.4 – 2.0) | 2.1 (1.6 – 2.5) | 1.9 (1.3 – 2.4) | 1.9 (1.5 – 3.0) |
| Triglycerides (mmol/L) |  | 1.76 (1.34 – 2.54) | 1.77 (1.16 – 2.21) | 1.70 (0.95 – 2.39) | 1.43 (1.26 – 1.79) |
| Non-esterified fatty acids (mmol/L) |  | 0.42 (0.36 – 0.62) | 0.41 (0.34 – 0.73) | 0.47 (0.35 – 0.58) | 0.48 (0.43 – 0.78) |
| Smoking status | Never smoked | 5 (29.4) | 8 (47.1) | 7 (41.2) | 10 (58.8) |
|  | Ex-smoker | 9 (52.9) | 9 (52.9) | 9 (52.9) | 5 (29.4) |
|  | Current smoker | 3 (17.7) | 0 (0) | 1 (5.9) | 2 (11.8) |
| C-reactive protein (mg/L) |  | 5.0 (5.0 – 6.5) | 5.0 (5.0 – 5.0) | 5.0 (5.0 – 5.0) | 5.0 (5.0 – 5.0) |
| *Appetite-regulatory peptides* |  |  |  |  |  |
| Fasting total PYY (pg/mL) |  | 87 (60 – 110) | 83 (65 – 108) | 74 (59 – 109) | 72 (53 – 93) |
| Postprandial total PYY (pg/mL)\* |  | 125 (93 – 182) | 140 (120 – 185) | 128 (105 – 198) | 133 (91 – 159) |
| Fasting acylated ghrelin (pg/mL) |  | 43 (26 – 85) | 34 (28 – 53) | 78 (34 – 92) | 64 (35 – 92) |
| Postprandial acylated ghrelin (pg/mL)\* |  | 20 (13 – 55) | 18 (11 – 32) | 34 (17 – 51) | 27 (17 – 75) |
| Fasting total GLP-1 (pmol/L) |  | 32 (22 – 42) | 33 (25 – 36) | 30 (22 – 48) | 30 (25 – 36) |
| Postprandial total GLP-1 (pmol/L)\* |  | 47 (40 – 51) | 42 (38 – 53) | 46 (34 – 61) | 44 (32 – 51) |
| Fasting leptin (ng/mL) |  | 15.3 (7.6 – 32.3) | 14.9 (9.4 – 16.7) | 23.0 (11.1 – 30.3) | 10.7 (7.7 – 36.7) |
| *Three-factor eating questionnaire dimensions* |  |  |  |  |  |
| Cognitive restraint (AU) |  | 25 (22 – 29) | 26 (22 – 29) | 28 (21 – 32) | 29 (23 – 33) |
| Disinhibition (AU) |  | 9 (8 – 14) | 14 (8 – 17) | 15 (7 – 18) | 10 (9 – 14) |
| Hunger (AU) |  | 10 (8 – 11) | 11 (10 – 14) | 11 (10 – 16) | 10 (8 – 13) |

Continuous and categorical data presented as median (interquartile range) and frequency (%), respectively. \*calculated as time-averaged area under the concentration-time curve during the standardised 3-hour mixed meal tolerance test. Abbreviations: AU, arbitrary units; eGFR, estimated glomerular filtration rate; GLP-1, glucagon-like peptide-1; HbA1c, glycated haemoglobin; PYY, peptide YY.

**Table 2 – Primary and key secondary outcomes: differences between experimental groups (placebo-plus-diet, empagliflozin-only, and empagliflozin-plus-diet) and placebo-only at 24 weeks**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Placebo-plus-diet** | | | **Empagliflozin-only** | | | **Empagliflozin-plus-diet** | | |
|  | N | *β*-coefficient [95% CI] | *p*-value | N | *β*-coefficient [95% CI] | *p*-value | N | *β*-coefficient [95% CI] | *p*-value |
| *Primary outcome* |  |  |  |  |  |  |  |  |  |
| Postprandial total PYY (pg/mL)\* – complete case | 14 | -8.6 [-28.6 to 11.4] | 0.400 | 15 | 13.4 [-6.1 to 33.0] | 0.179 | 17 | 1.0 [-18.0 to 19.9] | 0.920 |
| Postprandial total PYY (pg/mL)\* – ITT | 17 | -7.3 [-27.2 to 12.5] | 0.468 | 17 | 12.5 [-7.2 to 32.3] | 0.213 | 17 | 1.0 [-18.1 to 20.0] | 0.921 |
| Postprandial total PYY (pg/mL)\* – per protocol | 8 | 9.4 [-17.2 to 35.9] | 0.489 | 12 | 29.3 [6.5 to 52.1] | **0.012** | 13 | 7.7 [-15.1 to 30.4] | 0.510 |
| *Secondary outcomes* |  |  |  |  |  |  |  |  |  |
| Appetite-regulatory peptides, subjective appetite perceptions and three factor eating questionnaire dimensions |  |  |  |  |  |  |  |  |  |
| Postprandial acylated ghrelin (pg/mL)\* | 14 | 3.2 [-17.7 to 24.1] | 0.765 | 15 | -13.8 [-34.3 to 6.7] | 0.187 | 17 | -13.5 [-33.5 to 6.5] | 0.185 |
| Postprandial total GLP-1 (pmol/L)\* | 14 | 1.2 [-4.1 to 6.6] | 0.657 | 15 | 3.1 [-2.2 to 8.3] | 0.250 | 17 | 0.3 [-4.8 to 5.5] | 0.896 |
| Fasting leptin (ng/mL) | 14 | -1.2 [-5.5 to 3.1] | 0.588 | 15 | 0.6 [-3.6 to 4.9] | 0.774 | 17 | -4.8 [-8.9 to -0.7] | 0.022 |
| VAS – Postprandial hunger (mm)\* | 14 | -2.6 [-13.4 to 8.2] | 0.634 | 14 | 7.5 [-3.2 to 18.3] | 0.171 | 17 | 3.6 [-6.6 to 13.8] | 0.488 |
| VAS – Postprandial fullness (mm)\* | 14 | 3.9 [-8.4 to 16.3] | 0.534 | 15 | -1.2 [-13.1 to 10.8] | 0.850 | 17 | -3.5 [-15.1 to 8.1] | 0.556 |
| VAS – Postprandial satisfaction (mm)\* | 14 | 5.4 [-7.2 to 17.9] | 0.401 | 15 | 1.3 [-11.0 to 13.6] | 0.833 | 17 | -5.7 [-17.6 to 6.1] | 0.344 |
| VAS – Postprandial prospective food consumption (mm)\* | 14 | -0.5 [-11.3 to 10.2] | 0.922 | 15 | 3.0 [-7.3 to 13.3] | 0.564 | 17 | 3.1 [-6.9 to 13.1] | 0.539 |
| TFEQ – Cognitive restraint (AU) | 14 | 2.9 [-0.1 to 5.9] | 0.056 | 16 | 1.4 [-1.5 to 4.3] | 0.349 | 17 | 4.6 [1.7 to 7.5] | **0.002** |
| TFEQ – Disinhibition (AU) | 14 | -0.1 [-2.0 to 1.8] | 0.931 | 16 | 0.4 [-1.4 to 2.2] | 0.679 | 17 | 0.6 [1.1 to 2.4] | 0.475 |
| TFEQ – Hunger (AU) | 14 | -0.2 [-1.9 to 1.5] | 0.825 | 16 | 0.8 [-0.9 to 2.4] | 0.367 | 17 | -0.7 [-2.3 to 0.8] | 0.364 |
| Anthropometry and body composition |  |  |  |  |  |  |  |  |  |
| Body weight (kg) | 14 | -1.52 [-3.79 to 0.76] | 0.191 | 16 | -2.23 [-4.45 to -0.01] | 0.049 | 17 | -5.62 [-7.79 to -3.44] | **<0.001** |
| Total fat mass (kg) | 14 | -1.94 [-3.72 to -0.16] | 0.033 | 16 | -0.98 [-2.71 to 0.74] | 0.264 | 17 | -4.06 [-5.76 to -2.36] | **<0.001** |
| Total lean body mass (kg) | 14 | 0.34 [-0.50 to 1.18] | 0.428 | 16 | -1.41 [-2.23 to -0.60] | **0.001** | 17 | -1.60 [-2.40 to -0.80] | **<0.001** |
| Energy balance and habitual physical activity |  |  |  |  |  |  |  |  |  |
| Daily energy intake (kcal/day) | 15 | 226 [-82 to 535] | 0.151 | 14 | 252 [-56 to 560] | 0.109 | 13 | 210 [-112 to 532] | 0.202 |
| Resting energy expenditure (kcal/day) | 13 | -80 [-261 to 101] | 0.387 | 16 | -129 [-297 to 40] | 0.134 | 17 | -212 [-378 to -45] | **0.013** |
| Steps (number/day) | 13 | 604 [-698 to 1906] | 0.363 | 15 | -800 [-2047 to 447] | 0.209 | 14 | 574 [-695 to 1843] | 0.375 |
| Sedentary time (min/day) | 13 | -23 [-65 to 19] | 0.283 | 15 | 1 [-40 to 41] | 0.974 | 14 | -18 [-59 to 23] | 0.395 |
| Light-intensity physical activity (min/day) | 13 | 20 [-15 to 56] | 0.261 | 15 | -2 [-36 to 32] | 0.909 | 14 | 10 [-24 to 45] | 0.558 |
| Moderate-to-vigorous-intensity physical activity (min/day) | 13 | 3 [-9 to 15] | 0.586 | 15 | -1 [-13 to 11] | 0.863 | 14 | 7 [-5 to 19] | 0.249 |
| Glycaemic control |  |  |  |  |  |  |  |  |  |
| HbA1c (mmol/mol)† | 14 | -1.4 [-5.5 to 2.7] | 0.512 | 16 | -4.4 [-8.3 to -0.4] | 0.032 | 17 | -4.8 [-8.7 to -0.9] | **0.016** |
| Fasting plasma glucose (mmol/L) | 13 | -0.05 [-0.63 to 0.53] | 0.872 | 16 | -0.88 [-1.44 to -0.31] | **0.002** | 17 | -1.23 [-1.78 to -0.69] | **<0.001** |
| Postprandial plasma glucose (mmol/L)\* | 14 | 0.06 [-1.12 to 1.24] | 0.919 | 15 | -1.24 [-2.40 to -0.08] | 0.036 | 17 | -1.66 [-2.78 to -0.53] | **0.004** |
| Fasting plasma insulin (mU/L) | 14 | -1.2 [-5.7 to 3.3] | 0.613 | 15 | -4.4 [-8.7 to 0.0] | 0.048 | 17 | -4.3 [-8.6 to 0.0] | 0.048 |
| Postprandial plasma insulin (mU/L)\* | 14 | -26.8 [-45.7 to -7.9] | **0.006** | 15 | -32.3 [-51.4 to -13.3] | **0.001** | 17 | -20.9 [-38.9 to -2.9] | **0.023** |
| Postprandial glucagon (pg/mL)\* | 14 | -5.5 [-20.1 to 9.1] | 0.461 | 15 | -4.6 [-18.9 to 9.7] | 0.530 | 17 | -6.5 [-20.4 to 7.5] | 0.363 |

Analyses conducted using a complete-case approach unless otherwise specified, with generalised linear models adjusted for age, BMI (both categorised as per randomization) and baseline value of the outcome; *p*-values in bold are statistically significant (assessment of statistical significance used the Holm sequential Bonferroni procedure to account for multiple comparisons); \*calculated as time-averaged area under the concentration-time curve during the standardised 3-hour mixed meal tolerance test. †statistical analyses of HbA1c were performed on data in mmol/mol only. Converted values of within-group change and between-group differences in % can be found in Supplementary Table 4. Abbreviations: AU, arbitrary units; GLP-1, glucagon-like peptide-1; HbA1c, glycated haemoglobin; ITT, intention-to-treat; PPY, peptide YY; TFEQ, three-factor eating questionnaire; VAS, visual analogue scale.

**Figure 1 – Study consort diagram**



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Description automatically generated**Figure 2 – Difference between experimental groups and placebo-only at each timepoint (open symbols) and across follow-up (filled symbols) in appetite-regulatory gut peptides: (A) postprandial total PYY, (B) postprandial acylated ghrelin, (C) postprandial total GLP-1, and (D) fasting leptin.**

**Figure 3 – Difference between experimental groups and placebo-only at each timepoint (open symbols) and across follow-up (filled symbols) in (A) total body weight, (B) resting energy expenditure, (C) daily steps, and (D) HbA1c.**

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