Proceedings of the Nutrition Society (2020), **79**, 357–366 doi:10.1017/S0029665120007028

First published online 10 June 2020

The Nutrition Society Summer Meeting was held at the University of Leeds, UK on 10–12 July 2018

Conference on 'Getting energy balance right'
Plenary Lecture 4

A review of the short- and long-term impact of weight loss on appetite in youth: what do we know and where to from here?

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This review seeks to synthesise our knowledge about changes in hunger and satiety that occur during diet-induced weight loss and during weight loss maintenance, with a particular focus on youth with obesity. Mechanisms of appetite responses to weight loss rely heavily on the adult literature. Physiological mechanisms that control appetite and satiety via the gut–brain axis have been elucidated but we have an incomplete picture of changes in gut hormones and peptides in youth with obesity. In adolescents, the role of the brain in long-term sensing of body composition and modifying appetite and satiety changes is easily over-ridden by hedonic influences for the reward of highly palatable sweet foods and encourages over-consumption. Accordingly, reward cues and hyper-responsiveness to palatable foods lead to a pattern of food choices. Different reward systems are necessary that are substantial enough to reward the continued individual effort required to sustain new behaviours, that need to be adopted to support a reduced body weight. Periods of growth and development during childhood provide windows of opportunity for interventions to influence body weight trajectory but long-term studies are lacking. More emphasis needs to be placed on anticipatory guidance on how to manage powerful hedonic influences of food choice, essential to cope with living in our obesogenic environment and managing hunger which comes with the stronger desire to eat after weight has been lost.

Obesity in youth: Appetite: Energy: Satiety: Weight loss

Prevalence of obesity in youth

Obesity occurring during childhood is not a recent phenomenon but its prevalence has shown a rapid upward trajectory over the past 40 years, now estimated to be 20–30 %, in many countries[1]. In 2016, childhood obesity is reported to impact 50 million girls and 74 million boys and the prevalence in parts of the world and Asia in particular, continues to climb[2]. Obesity tracks from childhood, through adolescence and into adulthood[3] bringing with it an increased risk of chronic disease. The rise of obesity and its co-morbidities has been a driver of research-based interventions designed to assist the already obese child and their family achieve a healthier body weight without a negative impact on psychological functioning such as self-esteem and self-worth[4].

Childhood is a unique period of lifespan where linear growth and sexual maturation takes place alongside psychological development. The literature that specifically examines the development of physiological control

Abbreviations: FFM, fat-free mass; FM, fat mass; TEE, total energy expenditure; VLED, very low-energy diet.

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systems of appetite and satiety mechanisms during childhood is sparse. Therefore, it is necessary to review the adult literature where exploration of appetite mechanisms in both the obese and non-obese state provides the best available evidence and examine these in relation to information available in children.

This review seeks to synthesise our knowledge about changes in appetite and satiety that occur during diet-induced weight loss and during weight loss maintenance, with a particular focus on youth with obesity. By understanding both physiological and psychological factors that impact on appetite, content of weight loss interventions can be informed which can provide participants with information about what they may expect in terms of changes to their feelings of hunger and fullness that follow diet-induced weight loss, and to better prepare them for weight loss maintenance.

Background: the physiological systems controlling appetite and satiety

Frayn[5] eloquently describes how metabolic regulation occurs in adults and there is no doubt that energy balance, and weight stability during adulthood, is possible for some but not all. In weight stable individuals, homoeostatic mechanisms which regulate food intake via control of appetite and satiety responses must be aligned with energy expenditure, a necessarily dynamic process with shifts perhaps even on a daily basis, which long-term serve to control body weight. The work of Blundell and colleagues has been pivotal in our understanding of the various inter-related physiological and behavioural elements that manage energy balance in human subjects, and in the obese state[6–8]. Fig. 1 provides an overview of the main physiological factors elucidated to date, that are involved in the short- and long-term regulation of appetite control systems. This figure includes the emerging area of the gut microbiome and its potential role in mediating signals via the gut–brain axis[9].

As shown in Fig. 1, the central control of appetite and satiety is in the arcuate nucleus of the hypothalamus. The arcuate nucleus is the major processing centre receiving short-term signals, both stimulatory and inhibitory, via multiple hormones and peptides produced in the gut in response to food intake; these are either orexigenic or anorexigenic in their action. The subsequent cross-talk between these episodic signals from the gut is released in response to feeding and their actions on the brain serve to regulate short-term hunger. Ghrelin is often referred to as the 'hunger hormone' and increasing levels of ghrelin drive individuals to eat food, satiety hormones such as cholecystokinin, glucagon-like peptide-1 and peptide YY signal 'stop eating', although there is no doubt that there is marked individual responsiveness to these gut hormones and peptides in adults.

Leptin is produced in adipocytes and circulating levels are positively associated with higher adiposity. Leptin shows circadian fluctuations and signals the brain about long-term energy stores. Plasma leptin levels in healthy weight individuals rise after eating and fall in the fasting state, thus influencing hunger and satiety. The pivotal role of leptin was verified via the very rare heritable condition of congenital absence of leptin, which results in early life hyperphagia with impaired satiety. Without leptin, the signal to 'stop eating' is missing and this lack of satiety drives chronic over consumption of food; fortunately, the obese state can be reversed when exogenous leptin is provided[10]. Case studies of leptin replete adolescents studied via MRI of the brain superbly demonstrate the role of the hypothalamus in both the acute and long-term food reward systems, both of which are mediated by leptin[11].

Body composition is a key component of our understanding of appetite regulation as it is part of a two way and long-term feedback mechanism. Fat mass (FM) is sensed via leptin which signals the arcuate nucleus and provides a long-term indicator of the nutritional state of the individual. In adults, sensing of body composition, and in particular the relative volume of FM and fat-free mass (FFM) impacts on total energy expenditure (TEE)[7]. Energy expenditure is related to body composition and in particular the volume of FFM and provides the other side of the energy balance equation, both via resting energy expenditure and energy expended via activity or exercise. Theoretically, if there was accurate coupling between energy intake and energy expenditure in adults that would result in weight stability.

Growth and development

Major growth periods in childhood are during the first 12 months of life, where birth weight can triple, and during the adolescent years which herald a period of linear growth. Puberty is driven by the production of sex hormones which stimulate skeletal growth, drive sexual maturation and changes in body composition with both increases in lean mass and FM. These occur amid a milieu of other endocrine changes; a rise in insulin resistance and increases in growth and thyroid hormones. Of particular relevance in long-term appetite control is the proportional increase in FM, occurring in early adolescence in males and later adolescence in females, which predisposes the adolescent years as a window where weight gain can easily exceed ideal, especially as it coincides with a decrease in voluntary physical activity[12]. Girls with obesity often enter puberty earlier than their healthy-weight peers, which may be mediated in part by increased leptin production due to excess adiposity[13] but there remains insufficient data in boys to establish a link between the secular trend in earlier puberty and increased adiposity.

Lifestyle factors influencing adiposity and appetite

Exercise, energy expenditure and energy intake

Exercise can increase energy intake by modulating the appetite control system towards an increased drive to eat, as a result of an increase in orexigenic signals, or

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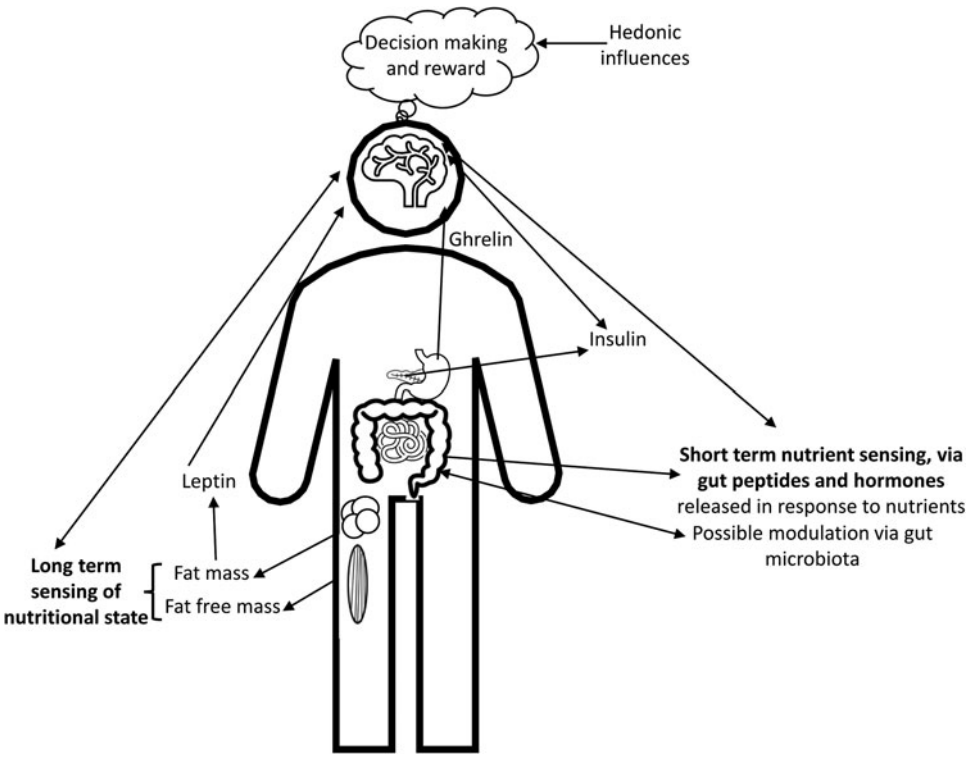

Fig. 1. Schematic representation demonstrating key aspects of appetite regulation.

an increased meal size and/or frequency as a result of reduced satiation and/or satiety[14]. In adults, habitual exercise has been shown to impact on appetite responses, and can sensitise at the individual level appetite and satiety responses for accurate coupling between energy intake and energy expended during exercise[15]. Exercise can also modulate energy intake via non-physiological processes and change the reward value associated with food. In controlled experimental designs using exercise to induce weight loss in adults with obesity, some individuals' response to exercise was an increase in their desire to eat high-fat sweet foods, and those responding in this manner were less successful in reducing their body fat using exercise[16]. In children, evidence is less convincing. As reviewed in 2014 by Thivel and Chaput[17], the dynamic relationship between physical activity and energy intake in both lean and children with obesity consistently shows a lack of agreement between food intake and appetite sensations after exercise demonstrating an uncoupling between exercise and subsequent energy intake.

Cheng *et al.*[18] described energy expenditure in adolescents of a healthy weight in a systematic review, and chart changes in resting energy expenditure and TEE over the period of sexual maturation[19]. The meta-analysis demonstrated that total daily energy expenditure was on average 16 % higher (range: 5–40 %) between pre-pubertal and pubertal groups. Thivel *et al.* in 2013[20] reviewed energy expenditure in children and adolescents to understand if energy expended via activity (including sedentary activity) was a driver of food energy intake. Methodological differences between studies included in this review made drawing firm conclusions challenging; however, Thivel concluded that energy expenditure is not the main driver of energy intake in either lean or obese youth. These findings are inconsistent with work by Blundell *et al.* in adults, who concluded that the proportional volume of FM and FFM modulates energy intake[21,22].

It would seem logical that a period of rapid growth and development would be sufficient to increase hunger and stimulate food energy intake. A review by Cheng *et al.*[18] highlighted the lack of studies which had employed objective methods of measuring food (energy) intake at mealtimes in adolescents, citing only one study by Shomaker *et al.*[23] as being sufficiently robust in quality to contribute data. Shomaker *et al.*[23] studied the voluntary food intake of 204 children across the pubertal stages on two occasions using an *ad libitum* buffet lunch design with direct observation of individual participant food intake to objectively record food intake. Pubertal males and females both consumed more energy than their pre-pubertal peers (males 41 % and females 25 %) but when adjusted for body composition these were no longer significant. After adjusting for pubertal stage, height, overweight status, body composition, race and meal instruction, males consistently consumed significantly more food energy than females. This single study indicates that sex differences in hunger and fullness could exist during puberty. However, due to the dearth of longitudinal studies, it remains unknown whether alterations in appetite occur at different chronological ages for males and females or other factors, yet to elucidated, support an increase in food intake which coincide with the additional energy needs to support linear growth.

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Sleep

Sleep duration and quality has been a very recent lifestyle issue that has come to attention in relation to food choices and appetite. This is in part because of the exponential rise in time spent with hand-held devices and screen time and concomitant communicant increase in time spent in sedentary behaviour. These factors alone have been blamed for the childhood obesity epidemic[24]. Sleep is perhaps the final part of the jigsaw puzzle around lifestyle and its impact on food choices. Weiss *et al.*[25] reported that short sleep duration in healthy weight adolescents was associated with an increase in hedonic desire and consumption of high-fat foods and unhealthy snacks. These findings were supported by a crossover trial conducted by Beebe *et al.*[26] who reported that short sleep duration (6·5 h in bed/night) was associated with higher intake of sweets and desserts, compared to 'healthy sleep' (10 h/night)[26]. The mechanism for such alterations driven by a lack of sleep is via the brain reward system, and that shortened sleep may drive reward systems towards a desire to seek food as a reward. Jensen *et al.*[27] using fMRI confirmed adolescents who had short sleep duration (5 h in bed for five nights) have higher activation in food-reward processing regions of the brain. However, in those who were healthy weight, there was a simultaneous increase in activity in inhibitory regions, whereas in those with obesity this increase was not observed. Therefore, regardless of weight status food reward increases, but this impact may be moderated by weight status-related inhibition[27].

Hedonic factors and risk taking

Food choice is not just about responding to physiological signals to hunger and satiety, hedonic factors play a substantial role. The psychological literature contributes to our understanding of hedonic factors and explores why human subjects choose to eat the food they do; this pathway takes us back to the brain being the major controller of appetite and satiety. Amongst its many functions, the brain is involved in decision-making and how human subjects estimate the risk and reward with regards to eating and the brain then assesses the impact of these choices on health. Research in this field is evolving but provides some tantalising clues as to how young adults may be challenged by the obesogenic environment that surrounds them and how they weigh up the risk of choosing healthy foods. To explore risk taking in the context of food choices it is necessary to examine how the brain responds to various food cues and tasks which has been achieved using fMRI studies.

In adults, there are associations between higher BMI and greater activation of brain regions involved in reward when making choices between low and high energy drinks and weaker activation of brain areas involved in energy regulation[28]. Moreno-Padilla *et al.* compared the brain activity between adolescents with a healthy weight *v.* overweight, reporting that there was greater brain reactivity on reward regions including emotional responsiveness to food in the higher weight adolescents[29]. Risky decision-making tends to be characterised by the need to receive an immediate reward, such as the immediate pleasurable taste of a high-fat high-sugar snack item, which over-rides the perceived risk associated with eating that item. However, we do not know if this weaker activation is a cause or a consequence of the obese state, an area worthy of further research.

Mata *et al.* in 2016[30] reported in a controlled study in which 16 adolescents (age 12–18 years) with obesity were asked to complete a validated risk-taking task, whilst in a fMRI scanner, before and after a 3-month weight loss attempt. The results demonstrated that it was possible to differentiate successful weight loss from those who were not so successful via the responses and greater activation of the anterior insula of the brain; this suggests that the brain is sensitive to the obese state and controls risk behaviours. In another study, Mata *et al.* were able to predict successful weight loss, as well as attrition, in young adults attending a weight loss programme in a university setting via measuring responsiveness to effort-based decision making, risk and reward tasks. Those successfully completing the short 12-week weight loss intervention were more likely to expend effort for uncertain reward than those who did not complete[31].

Zald in 2009 hypothesised how individuals view risk with regards to food choices, proposing that the risk of eating an unhealthy food item is estimated on a meal by meal basis[32]. This means that at an individual level, the risk associated with eating a single unhealthy food item would be viewed as quite small whilst the cumulative risk of choosing an unhealthy dietary pattern is not necessarily considered.

This emerging evidence of differences in risk taking and emotional responses to food in the obese state compared to healthy weight state would suggest that the hedonic factors are substantial drivers of the ingestive behaviour in adolescents and this is related to body composition, specifically percentage body fat.

Outcomes from weight loss interventions in youth

Reversing the already obese state is not simple, either at a group or at an individual level, in youth with obesity. Numerous research-based weight loss interventions have been well described and synthesised using Cochrane methodologies. Recent reviews for children[33], adolescents[34] and parent-focused interventions, have been designed to impact the diet and activity of very young children[35] but few have follow-up past 1 year duration.

Colquitt *et al.*[33] synthesised outcomes from 529 preschool children from seven randomised-controlled trials and reported a mean greater reduction of −0·3 units BMI *z*-score in those exposed to a multi-component intervention (diet, activity and behaviour) compared to control groups. Only one trial providing low-quality evidence reported follow-up after 2 years, with a mean difference of −0·3 units.

Loveman *et al.*[35] reported on interventions delivered to parents of very young children but their widely differing approaches and use of comparator groups made meta-analysis difficult. Nevertheless, in the longest

https://doi.org/10.1017/S0029665120007028 Published online by Cambridge University Press

follow-up period (9–12 months) a non-significant mean difference of 0·01 in BMI *z*-score change was found between the intervention and the minimal contact control group (one trial in 165 participants). Synthesis from the 2017 Cochrane review reporting data from five trials of adolescents (age 12–17 years, 602 participants) with a 1·5–2 year follow-up, resulted in a mean BMI *z*-score change of −0·34[34].

In 2019, a systematic review of systematic reviews synthesised outcomes from adolescent obesity interventions and concluded that a modest short-term reduction of BMI *z*-scores is consistently achieved across lifestyle interventions compared to wait list controls[36]. Most interventions, whether they be designed to restrict dietary energy intake, increase energy expenditure via activity or a combination of the two, on average result in a 3·7 kg reduction in weight/weight percentile after 12 months.

Adolescents with severe obesity may be considered for bariatric surgery. There are several different surgical procedures available. A systematic review in 2018, reported that reductions in BMI after 12 months were sustained at 3 years which varied with the procedure undertaken (gastric band −10·3 (95% CI −7·0, −13·7), −13·0 (95% CI −11·0, −15·0) after gastric sleeve, and −15·0 (95% CI −13·5, −16·5) BMI kg/m^2 after gastric bypass)[37]. Shoar *et al.* systematically reviewed longer-term outcomes (2–23 years) of 950 predominately female (73 %) adolescents (age: 12–19 years) with a pre-surgical BMI ranging from 26 to 91 kg/m^2 and reported an average BMI loss of 13·3 kg/m^2[38].

Trooboff *et al.*[39] synthesised the impact of bariatric surgery (various procedures including gastric banding) from fourteen studies (573 adolescents, age <21 years), on quality of life and reported significant improvements after 12 months of surgery, sustained at the longest follow-up (60 months)[39]. A review by Herget *et al.*[40] exposes the substantial psychological co-morbidities in youth with severe obesity (BMI 46·1–64·5 kg/m^2) which exist prior to bariatric surgery[40]. The reported prevalence of depression (15–70 %), anxiety (15–33 %) and disordered eating (48–70 %) serve to demonstrate the major negative psychological impact that severe obesity imparts on youth. After weight loss surgery, there was significant decline in symptomology for depression and anxiety but the impact on disordered eating was less clear with only two studies (thirty-five patients) reporting follow-up and both studies finding some elements of disordered eating persisting[40]. As in adults, bariatric surgery results in substantial weight loss in youth with severe obesity but it is not without risks. There is a dearth of data on nutritional implications, long-term growth and impact on appetite and satiety mechanisms in young people undergoing these procedures.

One of the major issues in synthesising evidence from youth weight management studies are the substantial differences in approach taken, designed to be culturally and age appropriate and delivered with intensity and duration of follow-up determined by resources rather than need. Although reflexive analysis can uncover what elements can predict successful weight loss and serve to highlight that elements of interventions such as early successful weight loss, those starting at a lower BMI and regular monitoring of weight[41,42] are helpful strategies in ensuring that those wishing to lose weight are given the best chance of success. Short-term success is often apparent but longer-term outcomes are substantially lacking in the literature to date; again we have to fall back on adult literature to explore potential mechanisms for long-term weight loss success or failure and how appetite and satiety mechanisms interconnect.

Weight recidivism

What we know from the adult literature is that weight recidivism is common. In US adults, it has been reported that one in six who have lost weight on their own manage to maintain at least a 10 % body weight loss at 1 year[43]. Therefore, weight loss maintenance is undoubtedly the biggest challenge in the management of the obese state[44,45]. However, in adults if treatment and support is continued, weight regain can be avoided[46]. Reasons for recidivism are complex, involving a combination of reduced motivation and compliance to energy restricted diets and exercise regimens[47,48], withdrawal of support by health professionals as intervention periods come to an end, plus the metabolic, neuroendocrine and autonomic adaptive responses that are hypothesised to oppose the reduced obese state leading to increased appetite and reduced satiety[49,50].

What can we learn from the adult literature that may help inform weight interventions directed at youth?

First, let's explore whether diet type matters or not. Diet-induced weight loss leads to a significant increase in hunger feelings and the release of the orexigenic hormone ghrelin[51,52] and this has been described in adults even when weight loss is minimal (1–2 kg)[53,54]. Rise in ghrelin and reductions in insulin after modest reductions in BMI in adolescents have also been reported[55,56]. Protein is regarded as the most satiating of macronutrients[57] and systematic reviews exploring protein as a pre-load in laboratory settings confirm that protein promotes greater satiety[58]. It is logical to explore the use of higher protein diets in maximising satiation to reduce the feelings of hunger during a weight loss attempt and extending inter-meal intervals (increasing satiety). When the literature is reviewed systematically in adolescents the evidence that macro-nutrient composition makes any substantial impact on weight loss *per se* and cardiometabolic outcomes is lacking[59] but this is not to say, that higher protein intakes cannot help children and adolescents manage hunger better, but to date there has been a dearth of data to support this assumption.

It is important to remember we do not eat nutrients but food, whether it be cooked and/or undergone processing will impact on digestion and assimilation of its macro-nutrient components. A discussion of nutrient sensing mechanisms in the gut is beyond the scope of this review. However, protein and the complexities of its digestion has been succinctly reviewed recently by Santos-Hernández[60] who describe the protein sensing

https://doi.org/10.1017/S0029665120007028 Published online by Cambridge University Press

role of the gut and subsequent release of ghrelin, cholecystokinin, glucagon-like peptide-1, glucagon-like peptide-2 and peptide YY, which are all impacted upon by the structure and nature of protein consumed.

How protein type may impact on satiety responses and energy expenditure in adolescents with obesity has been described in a short-term study using a pre-load paradigm by Nguo *et al.*[61]. In this acute cross-over study, overweight and healthy weight adolescents (age 11–19 years) were offered either a high carbohydrate (79 %) or a high-protein (55 %) meal and meal-induced thermogenesis and subjective appetite using visual analogue scales were measured over 4 h. The results showed increased fullness and higher meal-induced thermogenesis after the high-protein meal, but no differences in postprandial fullness between the overweight and healthy weight groups.

Using a very low-energy diet (VLED) with a known and more homogeneous macro-nutrient composition can provide some clues as to what happens to appetite and satiety hormones and peptides under more standardised conditions. When carbohydrates and/or energy (using a VLED) are restricted sufficiently to induce ketosis, the increase in appetite observed with weight loss seems to be absent in adults with obesity[62,63]. However, it seems that a transient increase in the drive to eat occurs up to 3 weeks (5 % weight loss) on a ketogenic VLED, despite no increase in active ghrelin. After that, and although participants are ketotic, no increase in appetite (from baseline) is observed up to a 17 % weight loss. However, hunger feelings and the plasma concentration of active ghrelin should be expected to increase significantly from baseline, once refeeding occurs and ketosis disappears[64].

A recent review of the efficacy of using VLED in children and adolescents with obesity concluded that a 10 kg weight loss was achieved with data drawn for twenty studies lasting 3–20 weeks. Longer-term follow-up up to 14·5 months showed mean weight losses of 5·3 kg[65]. Adolescents appeared to have the greatest benefit from BMI loss ($-5{\cdot}8$ kg/m^2 in two studies) and the authors concluded that VLED were effective but could not fully demonstrate safety due to adverse events not being well described suggesting caution in the use of these products unless medically supervised.

What is the impact of weight loss on appetite regulation systems?

In adults, it is well established that diet-induced weight loss is accompanied by several physiological changes on both sides of the energy balance equation, with an upregulation of appetite which stimulates energy intake[51,66], despite a reduced TEE[67]. The reduction in TEE is due to a decrease in both resting and non-resting energy expenditure, as a result of the reduced body mass and, in some cases, enhanced metabolic efficiency[67,68]. Leibel *et al.*[67] showed that a weight loss of only 10 % is followed by a reduction in TEE on average 1046 kJ larger than predicted for the newer lower body weight[67]. Additionally, hunger feelings and the plasma concentration of the orexigenic hormone ghrelin increase, whereas satiety has been reported to be reduced[53,69]. The increased appetite associated with weight loss has been estimated to be threefold larger than the corresponding reduction in TEE and proposed as the main driver of weight re-gain in adults[70].

In weight-reduced adolescents, Jensen *et al.* described a similar pattern of change in leptin alongside significant falls in plasma insulin which occur with very modest reductions of BMI ($-0{\cdot}5$ *z*-score BMI) after 12 weeks[56]. In Jensen's study, ghrelin did not alter but total amylin, gastric inhibitory polypeptide and pancreatic polypeptide reduced. Despite these physiological cues, using visual analogue scales to measure appetite, the 10–17-year olds did not report any changes in their overall appetite sensations. This reduction in satiety peptides would serve to drive weight re-gain. In a small sample of children with obesity, Deschamps[71] reported gastric inhibitory polypeptide levels to decrease after weight loss, which may be related to insulin secretion rather than be directly relevant to appetite control. In a larger and more recent community delivered intervention in children, Cohen *et al.*[72] described a reduction in leptin alongside changes in eating behaviour after 6 months using targeted messages about healthy eating and activity guidelines. However, it remains to be elucidated how reduced leptin concentrations modulate appetite regulation. To date, sample sizes in studies investigating changes in individual appetite hormones and responses to weight loss in children and adolescents have been very small and under-powered to demonstrate changes. A systematic review of studies exploring specific changes in ghrelin and peptide YY in acute studies using a single meal comparing obese with non-obese children provides stronger evidence that the child with obesity is responding differently to those of a healthy weight, with an attenuated responsiveness to peptide YY and ghrelin after 60 min. This difference in responsiveness is not in a helpful direction in terms of stimulatory effect on appetite[73], which may explain why children with obesity overconsume to reach satiety.

How quickly does the body defend weight loss?

In adults, a reduction of only 1–2 kg body weight has been shown to significantly reduce RMR, even below predicted values (a phenomenon known as adaptive thermogenesis) in some studies but others have reported no change[74,75]. A reduction in exercise-induced energy expenditure has been reported after 5 and 10 % body weight loss (10–13 kg)[68,75,76], in some cases below predicted values[76], whereas others have reported no change even after a 19 % reduction in body weight[77].

The timeline over which energy expenditure changes with progressive weight loss, has been studied in adults with obesity, and provides some clues as to potential mechanisms[78]. A study in adults with obesity, who had undergone a VLED, showed that RMR was significantly reduced at 5 % weight loss (674 (SE 121) kJ/d) and further reduction up to 16 % body weight did not change RMR significantly. Moreover, a reduction in RMR was sustained even after a period of weight stabilisation, which has been a consistent finding[67,79].

https://doi.org/10.1017/S0029665120007028 Published online by Cambridge University Press

Lazzer *et al.* reported in 2004[80] that an intensive 9-month weight reduction programme including an energy-restricted diet and exercise, resulting in a 17 kg body weight reduction in adolescents with severe obesity, induced a significant fall in basal, sleeping and sedentary metabolic rate, and TEE despite preservation of FFM. Moreover, a reduction in miscellaneous activities metabolic rate (washing, dressing, making the bed and tidying the room) and a trend towards a lower walking metabolic rate were also observed even after adjusting for changes in body weight. This study demonstrates that adaptive thermogenesis can occur in response to weight loss in adolescents, even though the minimum threshold of weight reduction needed to induce adaptive thermogenesis in this population has not been identified.

Coutinho *et al.* recently reported that the rate of weight loss and the nature of energy restriction (intermittent *v.* continuous) do not modulate the strength of the compensatory mechanisms previously described, after energy balance is reestablished[81,82].

Where to from here?

Evidence in adults of physiological feedback mechanisms that defend even small changes in weight loss highlights the need to develop anticipatory diet and activity guidance for those who are successful in losing weight in the short term to become successful weight loss maintainers. The small and inconsistent evidence base in children in relation to changes in gut hormones and peptides and how these alter with body composition would support the need for larger controlled studies to be conducted that would inform the mechanism of appetite control in youth with obesity. Studies to date in youth weight management lack long-term follow-up. This, along with the need to enhance reporting outcomes such as changes in body composition rather than simply body weight, are critically needed, if we are to unravel the interconnecting appetite systems that drive food intake in youth with obesity.

The simple lack of objective data on food intake in response to pubertal changes is also a gap in our knowledge and replication of a Shomaker[23] study would be helpful to further our understanding of whether growth periods such as pubertal do require an increase in food energy intake. Although it seems unlikely that diet type is important in weight loss *per se*, how we enhance the habitulisation of lifestyle behaviours that support weight loss maintenance is crucial. By exploring the behaviours of adolescents who have been successful in losing and then maintaining a lower body weight, it is clear that drivers for success need to be intrinsic such as the desire for better health[83] alongside the requirement for supportive family and peer groups[84]. Applying new knowledge from neuroscience provides clues that interventions must include tangible reward systems that are valued by the adolescent themselves to provide sufficient motivation to reward the effort required to make the daily choices that can support a lower body weight.

Methodological differences employed in appetite studies provide challenges for data synthesis and adoption of common measurement instruments would assist in the later interpretation of a body of literature. The acknowledgement that the wide variation in appetite responses within a group which potentially masks different phenotypes, should also inform future research[85]. In children who develop with a high proportion of body fat from early childhood through puberty may well be intrinsically different in their physiological and/or hedonic responses to food than their leaner counterparts.

An area of more recent research interest is the relevance and/or the clinical impact of the diversity of microbiota species in the gut which may impact on appetite and satiety mechanisms and is worthy of further study. Some tantalising findings from studies in early life show that weight trajectory of infants is associated with maternal body weight. Early life exposures such as mode of delivery and use of antibiotics have the potential to influence the development and the diversity of the microbiota[86,87]. There are apparent differences in gut microbiota between children with obesity and their lean counterparts[86] and changes in the diversity of species in gut microbiota in response to diet and exercise interventions in adolescents[88]. There is much we do not know about the gut microbiota and its potential for the gut–brain axis to be utilised in obesity prevention and/or treatment in youth with obesity.

In conclusion, this review finds substantial gaps in our knowledge and understanding of changes in the appetite regulation system in the obese state, in particular longitudinal studies after weight loss. These findings coupled with the recognition of the long-term effort required to adhere to a weight loss programme, with the multiple daily choices that need to succeed in weight loss needs consideration when planning treatment programmes for youth with obesity. More emphasis needs to be placed on anticipatory guidance on how to manage the powerful hedonic influences of food choice, that are required to cope with living in our obesogenic environment. Effective and helpful strategies on how to manage the short-term impacts on hunger and a stronger desire to eat after weight has been lost are critically needed if we are to support youth who wish to lose weight, to be successful in the long term.

Financial Support

This review received no specific grant from any funding agency, commercial or not-for-profit sectors.

Conflict of Interest

None.

Authorship

H. T. and C. M. drafted the paper and C. B. provided critical review.

https://doi.org/10.1017/S0029665120007028 Published online by Cambridge University Press

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