



Digestible nutrients and available (ATP) energy contents of two varieties of kiwifruit (*Actinidia deliciosa* and *Actinidia chinensis*)

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ABSTRACT

A model, which combines a dual *in vivo*–*in vitro* digestibility assay and stoichiometric relationships describing nutrient catabolism, has been recently developed to allow prediction of the available energy (AE) content of a food in terms of its ATP yield. The model uses the growing pig as an *in vivo* model for upper gastrointestinal tract digestion in humans. Terminal ileal digesta from the pig are incubated with human faecal inocula (*in vitro* fermentation model) to simulate human hindgut fermentation. The respective *in vivo* and *in vitro* digestibility assays provide predictions of the ileal absorbed and hindgut-fermented nutrient contents of a food which are then used to predict ATP production post-absorption, based on known stoichiometric relationships. In this study, the model was used to determine the AE contents of fresh, ripe Hayward (*Actinidia deliciosa* var Hayward) and Hort16A (*Actinidia chinensis* var Hort16A) kiwifruit. Kiwifruit pulp, containing 3 g kg⁻¹ of titanium dioxide, included as an indigestible marker, was fed to growing pigs and terminal ileal digesta were collected. Ileal nutrient digestibilities were determined. A sample of digesta was incubated *in vitro* with a fresh human faecal inoculum and the fermentable organic matter determined. The predicted available (ATP) energy contents of the Hayward and Hort16A kiwifruits were 5.9 and 6.2 kJ g⁻¹ dry matter, respectively, approximately 44–47% of the determined apparent digestible energy (ADE) content. The AE contents of the kiwifruit, expressed relative to the AE content of dextrin (a highly digestible source of glucose) were 0.57 and 0.61 for Hayward and Hort16A, respectively. Comparable ratios for metabolisable energy (ME) were 0.74 and 0.73. The predicted AE from kiwifruit was much lower than the predicted ME from kiwifruit when compared to dextrin. The ME values overestimate the energy content of kiwifruit that is available to the cell. AE was not only lower than ME but the two energy systems ranked the kiwifruit types differently in terms of energy supply to the body. The relatively low energy content per unit of dry matter and high water content of kiwifruit make kiwifruit an ideal weight loss food.

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1. Introduction

Determining the energy content of foods accurately is important and has direct application for weight control in humans. There are several measures of dietary energy that are currently used in practice, including apparent digestible energy (ADE) and metabolisable energy (ME) (Livesey et al., 2000). ADE is determined as the difference between dietary energy intake and faecal energy output while ME is determined as the difference between energy intake and the sum of faecal and urinary energy outputs. In practice, the ME content of a food is usually estimated using factorial or empirical models, such as the Atwater system or modified versions of the

Atwater system. Estimation of food energy values by the Atwater and similar systems is based on several assumptions which are not always tenable and recent evidence suggests that models which estimate the digestible or metabolisable energy content of foods may not be accurate, particularly in foods that are low in fat or high in fibre (Baer, Rumpler, Miles, & Fahey, 1997; Brown et al., 1998; Kruskall, Campbell, & Evans, 2003; Livesey, 1990; Zou, Moughan, Awati & Livesey, 2007). The energy values assigned in predictive ME models to dietary fibre and protein, in particular, are difficult to define generically, due to the diversity in chemical composition and digestibility (Ferrer-Lorente, Fernandez-Lopez, & Alemany, 2007; Livesey, 1990).

Calculating the available energy (AE) content of a food in the form of ATP delivered to the cell (Livesey, 1984) may be a more accurate measure of the energy value of a food than digestible or metabolisable energy (Coles, 2010). The prediction of ATP yields

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relies on being able to quantify the nutrients available for metabolism, based on uptake from the digestive tract, which should be determined separately in the upper tract and the large intestine (Coles, Moughan, Awati, Darragh, & Zou, 2010). Ideally, the most appropriate method for determining energy in foods for humans involves conducting *in vivo* trials with humans; however, it is not possible to obtain separate upper tract and hindgut measures *in vivo* in humans (Darragh & Hodgkinson, 2000). One approach is to use animal models to give the predicted upper tract absorption of each nutrient and to use *in vitro* fermentation assays (based on human faecal inocula) to predict short chain fatty acid production. This approach would allow the determination of energy uptake from different parts of the digestive tract, thus allowing consideration of differential efficiencies of nutrient utilisation (Coles et al., 2010). Such refinements are likely to become important when evaluating AE in foods containing high amounts of protein, resistant starch and fibre. The dual *in vivo*–*in vitro* digestibility approach was suggested by McBurney and Thompson (1987) and was subsequently validated by McBurney and Sauer (1993) and more recently by Coles et al. (2010), who compared organic matter digestibility for diverse diets determined using either the dual assay (rat, *in vitro*) or a human balance study.

Recently, Coles (2010) developed an AE model that extends the method of McBurney and Sauer (1993) to allow determination of ATP yield at the cellular level. This new model estimates the ATP available to the cell, based on the ileal digestible nutrient content determined, using a rat or pig (*in vivo*) model, hindgut-fermentable nutrient content, determined by the incubation of ileal digesta with human faecal inoculum (*in vitro* model) to simulate hindgut fermentation in humans, and the known stoichiometric relationships between absorbed nutrients and the ATP produced in the cell (Coles, 2010).

Kiwifruit is a fruit commonly consumed in western countries and its nutrient composition has been well characterised (Ferguson & Ferguson, 2003; Harman & McDonald, 1989; MacRae, Bowen, & Stec, 1989; MacRae, Lallu, Searle, & Bowen, 1989). Despite this, little is known about the digestibility of nutrients in kiwifruit or the AE derived from those nutrients. The nutrient composition of kiwifruit and its high fibre content suggest that kiwifruit should be a good weight loss food. In this study we applied the new assay, as described by Coles (2010), to determine the AE content of both Hayward (*Actinidia deliciosa* var *Hayward*) and Hort16A kiwifruit (*Actinidia chinensis* var *Hort16A*).

2. Materials and methods

2.1. Diet preparation

Fresh Hayward and Hort16A kiwifruit, pre-ripened to a similar degree of firmness (firmness RTE (ready to eat) of 0.5–0.8 kgf and 0.5–1.0 kgf, respectively), were prepared as follows: the skins of the Hayward kiwifruit were removed by hand and the flesh pulped using a kitchen food processor. The Hort16A kiwifruit was deskinning and the flesh pulped by cutting the kiwifruit into halves and putting the halves through a grinder (mesh size approximately 4 cm). The kiwifruit pulp was prepared fresh and stored at 4 °C for no more than 2 days.

2.2. *In vivo* studies

Ethics approval for the study was granted by the Massey University Animal Ethics Committee, Massey University, Palmerston North, New Zealand (application 08/43). Twelve Large White × (Large White × Landrace) entire male pigs of approximately 22.9 ± 0.1 kg body weight were obtained from a

commercial farm and housed individually in metabolism crates, in a temperature-controlled room at 22 ± 1 °C. The pigs had access to water at all times.

2.2.1. Determination of apparent ileal nutrient digestibility in kiwifruit

During a 14 day acclimatisation period, all pigs were fed a commercial cereal-based pig-grower diet at 10% of their metabolic body weight. At the beginning of each week, each pig was weighed and the dietary intake adjusted accordingly. The pigs received their daily ration as nine equal meals, one meal fed each hour between 08.30 and 16.30 h. At the end of the acclimation, the pigs were allocated, at random, to one of two treatments; Hayward kiwifruit or Hort16A kiwifruit. The kiwifruit flesh was gradually incorporated into the daily diet so that, by the end of the 14 day experimental period, each pig was consuming a diet that consisted of either 100% Hayward or Hort16A kiwifruit. The daily ration of kiwifruit dry matter was 10% metabolic body weight. Titanium dioxide (3 g kg⁻¹ of kiwifruit dry matter) was added to the diet on the final day (day 28) of the trial as an indigestible marker.

On day 28, 5–7 h after the start of feeding, each animal was sedated with midazolam (0.1 mg kg⁻¹) and ketamine (15 mg kg⁻¹) by intramuscular injection 20 min before commencement of general anaesthesia. The general anaesthesia was induced and maintained with isoflurane inhalation. The abdomen was opened by an incision along the mid-ventral line and the skin and musculature were folded back to expose the viscera. The section of the terminal ileum 20 cm anterior to the ileocaecal valve was dissected out. Blood was washed off the outside of the ileal section with deionised water and digesta were carefully flushed out into plastic bags using deionised water. The collected digesta were then frozen and stored at –20 °C prior to chemical analysis. The animal was euthanised while unconscious by severing of the portal vein and diaphragm.

2.2.2. Determination of *in vitro* dry matter and organic matter fermentability of kiwifruit

Fresh human faeces were collected from three healthy volunteers under anaerobic conditions. The volunteers had been eating an unspecified western diet and had received no antibiotic treatment for 3 months. Faeces (80 g) were immediately homogenised for 3 min with 250 ml of phosphate buffer (0.1 M at pH 7), filtered through six layers of cheesecloth to remove particulate matter and the material used immediately. The phosphate buffer was pre-boiled and then cooled under a stream of oxygen-free nitrogen and kept at 37 °C. Inoculum preparation was performed under a constant flow of CO₂.

Aliquots (5 ml) of inoculum were transferred to 50 ml McCartney bottles containing either 5 ml of phosphate buffer alone (blanks) or phosphate buffer with 100 mg of finely ground, homogenised terminal ileal digesta, obtained as described above. Each bottle was flushed with CO₂, capped and incubated at 37 °C for 24 h. After 24 h, the bottles were placed in an autoclave to stop fermentation. The dry matter and organic matter of the unfermented residue were then determined.

2.3. Chemical analysis

All analyses were carried out in duplicate. Dry matter, ash and total lipid were determined according to the methods described by AOAC (1995). Briefly, dry matter was determined gravimetrically after oven-drying overnight at 105 °C, while ash was determined gravimetrically after ashing at 500 °C overnight. Total lipid was determined gravimetrically after extraction in petroleum ether using a Soxtec solvent extraction system (Foss, Hillerød, Denmark). The total nitrogen content was determined on a LECO analyser (LECO Corporation, St. Joseph, Michigan, USA), using the

Dumas method (AOAC, 1995), and crude protein was calculated as the total nitrogen content multiplied by 6.25. Gross energy was determined by bomb calorimetry, using a LECO AC-350 Automatic Calorimeter (LECO Corporation, St. Joseph, Michigan, USA). Total dietary fibre was determined using an enzymatic–gravimetric method (AOAC, 2000). Sugars were determined using the phenol–sulphuric acid method (Gilles, Hamilton, Reber, & Smith, 1956) and starch was determined using a commercial kit (Total Starch Kit AA/AMG, Megazyme Australia, Sydney, Australia), which was based on the method of the AOAC, 2000. Titanium was determined by the method of Short, Gorton, Wiseman, and Boorman (1996).

2.4. Calculations

Nutrient flows at the terminal ileum were calculated using the following equation (units are $\mu\text{g g}^{-1}$ of dry matter intake (DMI)):

$$\text{Ileal nutrient flow} = \text{Ileal nutrient}(\mu\text{g g}^{-1} \text{ DM}) \times \frac{\text{Diet titanium}(\mu\text{g g}^{-1} \text{ DM})}{\text{Ileal titanium}(\mu\text{g g}^{-1} \text{ DM})}$$

Apparent ileal nutrient digestibility was calculated using the following equation: (units are $\mu\text{g g}^{-1}$ DMI):

$$\text{Apparent digestibility}(\%) = \frac{(\text{Dietary nutrient intake} - \text{Ileal nutrient flow})}{\text{Dietary nutrient intake}} \times 100$$

True ileal protein digestibility was calculated as follows: (units are $\mu\text{g g}^{-1}$ DMI):

$$\text{True digestibility}(\%) = \frac{(\text{Dietary protein intake} - (\text{Ileal protein flow} - \text{endogenous protein flow}))}{\text{Dietary protein intake}} \times 100$$

where the endogenous ileal protein flow was estimated for a high fibre diet (3.1 g kg^{-1}) based on the work of Hodgkinson, Moughan, Reynolds, and James (2000) and Schulze, van Leeuwen, Verstegen, and van den Berg (1995).

Ileal digestible nutrient content was calculated as follows: (units are g kg^{-1} DM):

$$\text{Ileal digestible nutrient content} = \text{Diet nutrient content} \times \text{Ileal nutrient digestibility}(\%)$$

Dry matter *in vitro* fermentability was calculated using the following equation: (units were g kg^{-1}):

$$\text{Dry matter(DM) in vitro fermentability}(\%) = \frac{(\text{DM}_{(\text{before in vitro fermentation})} - (\text{DM}_{(\text{after in vitro fermentation})} - \text{DM}_{(\text{faecal inoculum})}))}{\text{DM}_{(\text{before in vitro fermentation})}} \times 100$$

where the $\text{DM}_{(\text{faecal inoculum})}$ was estimated as the mean of the amount of faecal inocula dry matter present in blank bottles (containing faecal inocula but no digesta) after either no incubation or incubation for 24 h. Organic matter *in vitro* fermentability was calculated using the following equation: (units were g kg^{-1}):

$$\text{Organic matter(OM) in vitro fermentability}(\%) = \frac{(\text{OM}_{(\text{before in vitro fermentation})} - (\text{OM}_{(\text{after in vitro fermentation})} - \text{OM}_{(\text{in faecal inoculum})}))}{\text{OM}_{(\text{before in vitro fermentation})}} \times 100$$

where the $\text{OM}_{(\text{faecal inoculum})}$ was estimated as the mean of the amount of faecal inocula organic matter present in blank bottles (containing faecal inocula but no digesta) after either no incubation or incubation for 24 h. Apparent faecal energy digestibility was

calculated based on the *in vivo*–*in vitro* digestion assay using the following equation: (units were g kg^{-1} DMI):

$$\text{Apparent faecal energy}(\text{in vivo} - \text{in vitro assay})\text{digestibility}(\%) = \frac{\text{Dietary energy intake} - ((1 - \text{OM in vitro fermentability}/100) \times \text{ileal energy flow})}{\text{Dietary energy intake}}$$

Apparent digestible energy was calculated as follows: (units were kJ g^{-1} DM):

$$\text{Apparent digestible energy} = \text{Dietary energy content} \times \frac{\text{apparent faecal}(\text{in vivo} - \text{in vitro assay})\text{energy digestibility}(\%)}{100}$$

Metabolisable energy was calculated according to Zou, Moughan, Awati, and Livesey (2007) and based on the work of Brown et al. (1998) and Livesey (1991) (units were kJ g^{-1} DM):

$$\text{Metabolisable energy} = 16.7 \times (\text{protein} + \text{starch} + \text{sugars}) + 37.6 \times \text{fat} + 8.4 \times \text{total dietary fibre}$$

Available energy was calculated as follows:

$$\begin{aligned} \text{Available energy}(\text{kJ g}^{-1} \text{ DM}) &= \left[\sum (\text{Ileal digestible nutrient}_i(\text{g g}^{-1} \text{ DM}) \times \text{ATP yield}_i(\text{mol g}^{-1} \text{ DM})) \right. \\ &\quad + \text{in vitro fermentable organic matter}(\text{g g}^{-1} \text{ DM}) \\ &\quad \times \text{ATP yield}_{(\text{fermentable organic matter})}(\text{mol g}^{-1} \text{ DM}) \left. \right] \\ &\quad \times \text{Gibbs free energy for ATP} (57 \text{ kJ mol}^{-1}) \end{aligned}$$

where i = protein, lipid, starch, sugars and the ATP yields are those reported by Coles (2010): $\text{ATP yield}_{\text{protein}} = 131 \text{ mmol g}^{-1}$, $\text{ATP yield}_{\text{lipid}} = 407 \text{ mmol g}^{-1}$, $\text{ATP yield}_{\text{starch}} = 178 \text{ mmol g}^{-1}$, $\text{ATP yield}_{\text{sugars}} = 160 \text{ mmol g}^{-1}$, $\text{ATP yield}_{(\text{fermentable organic matter})} = 102 \text{ mmol g}^{-1}$.

2.5. Statistical analysis

Statistical comparisons were made across the two kiwifruit types using ANOVA (GLM procedure, SAS V9.1). Differences were considered significant at $P < 0.05$.

3. Results

The gross energy contents and the nutrient contents, including crude protein, total lipid, total sugars, total dietary fibre and starch of Hayward and Hort16A kiwifruit flesh were determined and are shown in Table 1. The nitrogen-free extractives (NFE) (carbohydrate) was also calculated as the difference between the dry matter and the sum of the ash, crude protein and total lipid. The sugar, NFE and gross energy contents were similar between the Hayward and Hort16A kiwifruit. The protein content of the Hort16A kiwifruit was 28% higher than that of the Hayward kiwifruit while the total dietary fibre and lipid contents were 27% and 87% higher, respectively, in the Hayward kiwifruit than in the Hort16A kiwifruit.

For the *in vivo* study, the pigs remained healthy throughout the experimental period, although mild faecal looseness was observed in some pigs at higher ($>40\%$) dietary concentrations of kiwifruit.

The apparent ileal digestibility of dry matter, organic matter, protein, total dietary fibre, starch, total lipid, total sugars and gross energy and the true ileal digestibility of protein for both Hayward and Hort16A kiwifruit flesh are shown in Table 2.

There was no significant ($P > 0.05$) difference in apparent digestibility between the Hayward and Hort16A kiwifruits for any of the nutrients with the exception of starch. Apparent ileal organic matter digestibility was significantly higher than apparent

Table 1

Nutrient composition (g kg⁻¹ dry matter) and gross energy (kJ g⁻¹ dry matter) of Hayward and Hort16A kiwifruit flesh.

Nutrient	Hayward kiwifruit	Hort16A kiwifruit
Crude protein	53	68
Total sugars	492	533
Total dietary fibre	170	134
Starch	3.1	3.7
NFE ^a	857	861
Total lipid	50	27
Minerals (total ash)	40	44
Gross energy	17.6	16.7

^a Nitrogen-free extractives (NFE) was determined as the difference between the dry matter and the sum of the ash, protein and ether extractives.

ileal dry matter digestibility for both Hayward ($P < 0.001$) and Hort16A ($P < 0.001$) kiwifruit. Overall, apparent ileal dry matter and organic matter digestibility were 58.7% and 62.0%, respectively, for Hayward and 59.6% and 64.0%, respectively, for Hort16A. Apparent ileal lipid digestibility was low for both varieties of kiwifruit (29–34%). The apparent ileal digestibility of total dietary fibre was not significantly ($P > 0.05$) different from zero for both kiwifruit varieties. Apparent ileal sugar digestibility was in excess of 95%, while starch digestibility ranged from 57% to 83%, depending on the kiwifruit variety, with the starch in the Hort16A kiwifruit being digested to a greater degree in the upper digestive tract than that in the Hayward kiwifruit. The apparent ileal protein digestibility was low (22–37%) but the true ileal protein digestibility was considerably higher (approximately 58–65%).

The *in vitro* fermentability of dry matter was not significantly ($P > 0.05$) different between the two kiwifruit varieties (43.8% and 41.6% for the Hayward and Hort16A kiwifruit, respectively). There was also no significant ($P > 0.05$) difference between the *in vitro* fermentability of organic matter determined in the Hayward and Hort16A kiwifruit (49.0% and 48.6%, respectively). Such fermentabilities are relatively low.

Organic matter excludes minerals, so organic matter fermentability more closely reflects the fermentation of fibre and other macronutrients (carbohydrate, protein and lipid) than does dry

matter fermentability. Consequently, the estimates of energy digestibility and availability were calculated based on the *in vitro* fermentation of organic matter. The apparent faecal digestibility of dry matter, organic matter and gross energy were predicted, using the (*in vivo*–*in vitro* assay) for the Hayward and Hort16A kiwifruit, and are shown in Table 3.

Predicted apparent faecal dry matter digestibility was approximately 76% and was significantly ($P < 0.01$), but only slightly, lower than predicted apparent faecal organic matter digestibility for both kiwifruit varieties. The predicted apparent faecal digestibility was significantly higher than the apparent ileal digestibility of dry matter ($P < 0.001$), organic matter ($P < 0.001$) and gross energy ($P < 0.001$).

The predicted ADE contents of the kiwifruit were estimated, using the *in vivo*–*in vitro* assay, and these data are shown in Table 4. In addition, ME values, calculated by modified Atwater factors, and available (ATP) energy, determined using the model (Coles, 2010), are also shown in Table 4. There was no significant ($P > 0.05$) difference between the kiwifruit varieties in ADE or available (ATP) energy contents estimated using the *in vivo*–*in vitro* assay. The available (ATP) energy content of both kiwifruit varieties was significantly lower ($P < 0.001$) than the ADE and was approximately half that of the calculated ME.

4. Discussion

The determined nutrient compositions of the Hayward and Hort16A fruits were similar to those previously reported for “ready to eat” kiwifruit (Ferguson & Ferguson, 2003). The apparent ileal digestibilities of dry and organic matter of both varieties of kiwifruit were low but were consistent with the apparent ileal digestibility determined factorially, based on protein, fat, sugars, starch and fibre digestibilities. Dry and organic matter digestibility values for different foods, determined using *in vitro* fermentation assays with human faeces, have resulted in a diverse range of values. Generally foods with higher insoluble fibre contents, such as cellulose, have low hindgut organic matter digestibility values (1.3%, Sunvold, Hussein, Fahey, Merchen, & Reinhart, 1995) and foods with

Table 2

Mean ($n = 6$) apparent ileal digestibility (%) of nutrients and true ileal protein digestibility (%) for Hayward and Hort16A kiwifruit flesh.

	Hayward kiwifruit	Hort16A kiwifruit	Overall SE	Significance
Dry matter	58.7	59.6	2.26	NS
Organic matter	62.0	64.0	2.12	NS
Protein	22.1	36.7	6.25	NS
Total dietary fibre	−2.7 ^a	−1.15 ^a	9.90	NS
Starch	57.3 ^b	82.7	3.36	***
Total lipid	28.7	33.5	7.69	NS
Total sugars	96.4	95.8	0.81	NS
Gross energy	55.2 ^c	57.7	2.66	NS
True ileal protein digestibility	58.2	65.0	6.25	NS

^a There was insufficient digesta to analyse total dietary fibre for all pigs fed each type of kiwifruit ($n = 5$). The small negative values determined indicate no digestion of fibre.

^b There was insufficient digesta to analyse starch for all pigs fed the Hayward kiwifruit ($n = 3$).

^c There was insufficient digesta to analyse gross energy for all pigs fed the Hayward kiwifruit ($n = 5$).

*** $P < 0.001$.

Table 3

Mean ($n = 6$) predicted apparent total tract digestibility^a (%) of dry matter, organic matter and gross energy for the Hayward and Hort16A kiwifruit.

	Hayward kiwifruit	Hort16A kiwifruit	Overall SE	Significance
Dry matter	76.8	76.4	1.31	NS
Organic matter	78.2	78.8	1.36	NS
Gross energy	77.1 ^b	78.2	1.38	NS

^a Predicted based on *in vivo* upper tract digestibility of energy and an *in vitro* estimate of hindgut organic matter digestibility.

^b There was insufficient digesta sample to analyse gross energy for all pigs fed the Hayward kiwifruit ($n = 5$).

Table 4

Predicted mean ($n = 6$) apparent digestible energy ($\text{kJ g}^{-1} \text{DM}$)^a, metabolisable energy ($\text{kJ g}^{-1} \text{DM}$)^b, available (ATP) energy ($\text{kJ g}^{-1} \text{DM}$) and available ATP (mol ATP kg^{-1}) of Hayward and Hort16A kiwifruit and of dextrin as a baseline.

	Apparent digestible energy	Metabolisable energy	Available (ATP) energy	Available ATP
Dextrin ^c	17.6	16.7	10.2	178
Hayward kiwifruit	13.6	12.5	5.9	104
Hort16A kiwifruit	13.1	12.2	6.2	109
Overall SE ^d	0.22		0.10	1.85
Significance	NS		NS	NS

^a Predicted based on *in vivo* upper tract digestibility of energy and an *in vitro* estimate of hindgut organic matter digestibility.

^b Metabolisable energy was calculated as described in Section 2. ME describes the energy that is digested, absorbed and metabolised in the body and is the energy available for total heat production and for body gains. It does not account for the energy cost of digestion and transport or the inefficiencies of ATP production.

^c Calculated apparent digestible energy, available energy, metabolisable energy and available ATP values for dextrin are included as reference values. Apparent digestible energy was calculated as the heat of combustion of 1 g of dextrin dry matter and assuming that digestion and absorption from the intestine were complete. Available energy and metabolisable energy were calculated as described in Section 2, based on the nutrient composition of dextrin and assuming complete digestion and absorption of the nutrients.

^d Statistical comparison between Hayward kiwifruit and Hort16A kiwifruit only.

higher soluble fibre contents, such as citrus pectin, have high hindgut digestibility values (85.2%, Sunvold et al., 1995). The apparent ileal digestibility of dry and organic matter, determined using the *in vitro* fermentation assay, was relatively low for both varieties of kiwifruit and this was likely due to a high insoluble fibre content of kiwifruit (S. Henare, unpublished data).

The apparent ileal digestibility of lipid was low (<35%) for both kiwifruit varieties and may result from an inability of the small intestine to digest either the oil-containing kiwifruit seeds or the structural lipids present in kiwifruit cell walls. The apparent ileal protein digestibility was also low (<37%) while true ileal digestibility estimates were approximately 58–65% for both Hayward and Hort16A kiwifruit protein. Proteins are present in both the cell wall and the soluble fractions of the edible part of kiwifruit (Tamburrini et al., 2005). The protein found in the soluble fractions should be readily digested (Lucas, Cochrane, Warner, & Hourihane, 2008) whilst the structural proteins found in the cell walls may be less available for enzymic digestion, due to their location and/or to the components to which they are bound. Regardless of this, the protein content of kiwifruit was low and protein would therefore contribute only a small proportion of the total available energy.

The total dietary fibre determined in both the Hayward and Hort16A kiwifruit was, as expected, undigested at the terminal ileum and this may have contributed to the relatively low digestibility values observed for DM, OM, lipid and protein. It has been shown that dietary fibre reduces the digestion and absorption of nutrients throughout the small intestine (Cumplings & Englyst, 1995), possibly by increasing digesta flow and thereby reducing the time during which digestion can take place (Bach Knudsen & Hansen, 1991). It is thought that the increased digesta flow associated with dietary fibre is due to the stimulatory effect the greater digesta bulk has on gut motility (LeGoff, Milgen, & Noblet, 2002).

The digestibility of energy is largely derived from the digestion and absorption of simple sugars, starch, lipid and protein in the small intestine and from fermentation (of mainly fibre and resistant starch) in the large intestine. In this study, apparent ileal energy digestibility was approximately 56% for both varieties of kiwifruit, and increased to approximately 78% (over the total tract) after fermentation was accounted for. ADE describes the energy derived from the nutrients in a food that have been digested and absorbed from the digestive tract. ME describes the energy that is digested, absorbed and metabolised in the body and can be determined experimentally or estimated using conversion factors such as the modified Atwater factors (Brown et al., 1998; Livesey, 1991). AE is the energy that is delivered to the cell and is available to power metabolic processes and can be estimated from the ATP yield derived from the absorbed nutrient content of a food (Coles et al., submitted for publication-a). The ADE, ME and AE were

Table 5

Metabolisable or available energy of Hayward and Hort16A kiwifruit expressed as a proportion of that in dextrin.

	ME ^a	Available energy ^b
Dextrin	1	1
Hayward	0.74	0.57
Hort16A	0.73	0.61

^a The proportion of kiwifruit ME to dextrin ME was calculated as follows: Proportion = $\text{ME}_{(\text{kiwifruit})} (\text{kJ g}^{-1} \text{DM}) / \text{ME}_{(\text{dextrin})} (\text{kJ g}^{-1} \text{DM})$ for each kiwifruit variety.

^b The proportion of kiwifruit AE to dextrin AE was calculated as follows: Proportion = $\text{AE}_{(\text{kiwifruit})} (\text{kJ g}^{-1} \text{DM}) / \text{AE}_{(\text{dextrin})} (\text{kJ g}^{-1} \text{DM})$ for each kiwifruit variety.

calculated for kiwifruit in this study and were also calculated for dextrin which was used here as a baseline reference (Table 4). The values for dextrin were calculated by assuming that the digestion of dextrin and the absorption of released glucose were complete. The lower ratio of AE to ADE observed for kiwifruit (0.45) compared to dextrin (0.57) is likely largely due to the presence of fibre in the kiwifruit since the ATP derived from fibre fermentation is less than that for the equivalent amount of protein, fat or digestible carbohydrate (Coles, 2010).

For both ME and AE, respectively, the ratio of the energy content of Hayward and Hort16A kiwifruit to that of dextrin was calculated (Table 5). Overall, the AE contents of both kiwifruit varieties were much lower than the ME contents when compared to dextrin. In addition, the ranking of the two varieties of kiwifruit in terms of the energy content in relation to dextrin, changed when the ratios were calculated from AE rather than ME. When ME values are used it would be predicted that the ME of kiwifruit, expressed as a proportion of the ME of dextrin, would be 0.73–0.74. However, the energy available to the cell in the form of ATP (AE) from kiwifruit relative to the AE from dextrin is predicted to be much lower (0.57–0.61). In addition, when ME values are used, it would be predicted that Hayward kiwifruit has a higher energy content than has Hort16A; however, based on AE, the reverse is true. In developing and evaluating foods specialized for weight loss application, the use of general factorial or empirical models, such as those used to estimate ME, is likely to be inaccurate (Zou et al., 2007) and the AE system described here has advantages. Weaknesses of the ME systems may also have important implications when evaluating energy balance and macronutrient intakes of the elderly or the ill.

There are no reported available or net ATP yields for fruits and vegetables other than those for kiwifruit, presented in this study. Coles et al. (submitted for publication-b) have, however, reported available and net ATP yields for three milk protein-based meal replacement formulations, two of which were specifically designed for weight loss. The available ATP yields, on a dry matter basis,

ranged between 121 and 160 mol of ATP per kg of meal replacer. In this experiment, the ATP yield for kiwifruit was lower, ranging from 104 to 109 mol kg⁻¹. This, and the relatively low nutrient digestibilities and relatively high water content, suggest that kiwifruit should be an excellent weight loss food.

5. Conclusion

In this study, a new assay was used to predict the AE content (in the form of ATP generated in the cell) of two kiwifruit cultivars, Hayward and Hort16A. In addition, ileal and faecal digestibilities of the macronutrients present in these cultivars were determined. On a dry matter basis, the high fibre content of both varieties of kiwifruit and the low digestibility of lipid, starch and protein suggest that kiwifruit would be a good food for weight loss. ADE and ME both overestimated the available (ATP) energy of kiwifruit, as expected, since neither ADE nor ME account for the inefficiencies of ATP production or the energy costs of digestion and transport. The current model, determining available (ATP) energy using the *in vivo*–*in vitro* assay, offers a more detailed and possibly more accurate description of the energy value of foods. It has particular relevance to evaluating weight-loss foods formulated to be high in nonstarch polysaccharides, protein and fibre. The AE system predicted very different relative energy yields (using dextrin as a baseline) in comparison with ME and led to different ranking of the foods. According to the AE system, kiwifruit is a much more effective weight loss food than would be concluded from the application of the modified Atwater ME system. Given that kiwifruit has a relatively low AE and also has a high water content, which will further reduce the energy density, kiwifruit appears to be a suitable food to include in diets designed for humans wishing to lose weight.

Disclosure statement

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