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Symposium 3: Importance of meal timing

Chrono-nutrition: a review of current evidence from observational studies on global trends in time-of-day of energy intake and its association with obesity

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The importance of the circadian rhythm in regulating human food intake behaviour and metabolism has long been recognised. However, little is known as to how energy intake is distributed over the day in existing populations, and its potential association with obesity. The present review describes global trends in time-of-day of energy intake in the general population based on data from cross-sectional surveys and longitudinal cohorts. Evidence of the association between time-of-day of energy intake and obesity is also summarised. Overall, there were a limited number of cross-sectional surveys and longitudinal cohorts that provided data on time-of-day of energy intake. In the identified studies, a wide variation in time-of-day of energy intake was observed, with patterns of energy distribution varying greatly by country and geographical area. In relation to obesity, eight cross-sectional surveys and two longitudinal cohorts were identified. The association between time-of-day of energy intake and obesity varied widely, with several studies reporting a positive link between evening energy intake and obesity. In conclusion, the current review summarises global trends in time-of-day of energy intake. The large variations across countries and global regions could have important implications to health, emphasising the need to understand the socio-environmental factors guiding such differences in eating patterns. Evidence of the association between time-of-day of energy intake and BMI also varied. Further larger scale collaborations between various countries and regions are needed to sum data from existing surveys and cohorts, and guide our understanding of the role of chrono-nutrition in health.

Circadian rhythms: Chrono-nutrition: Temporal trends: Obesity

Circadian rhythms are cyclical endogenous processes that occur with a periodicity of approximately 24 h. Research carried out in the 1970s identified a region in the brain of mammals within the anterior hypothalamus known as the suprachiasmatic nucleus. The suprachiasmatic nucleus also known as the master clock is

Abbreviation: TEI, total daily energy intake.
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synchronised to geophysical time via photic activation of the retinal ganglion cells. In this way, the suprachiasmatic nucleus can synchronise oscillators present within the cells of most organs and tissues, therefore influencing several physiological processes[1]. So although the importance of circadian rhythms in regulating mammalian physiological responses has been recognised for a long time[2], its impact on nutrition and metabolism is relatively new and is an area of evolving interest[3].

It is now well recognised that food intake, appetite, digestion and metabolism each exhibit circadian patterns[4]. Food intake itself serves as a regulator of the circadian clock, particularly the peripheral circadian clock in tissues such as the liver and the intestine[5–7]. Conversely, the central circadian clock, entrained by the dark–light cycle, is known to extend its effect on food absorption. More specifically, small peptides cleaved in the intestine from dietary protein have been shown to be transported in a circadian-driven process[8]. Similar observations have been made for glucose[9] and lipid transport[10]. However, despite our ever-growing knowledge of circadian rhythms, we still need to gain further insight into how the nutrient content of a mixed meal (macronutrient, micronutrient and energy content) may interact to benefit/compromise health.

The debate as to when to eat is imbedded in human history. Ancient Greeks consumed three to four meals, with breakfast and the evening meal being deemed most important[11]. In Roman times, breakfast was consumed at dawn although greater emphasis was given to eating later in the day particularly amongst the upper social classes[11]. By contrast, the poorer social classes ate their meals in line with the patterns of manual labour and thus consistent with the night–day cycle[11]. In the Islamic world, meal timing was also often dictated by the dark–light cycle. Consuming a meal before sunrise was deemed to be a sacred ritual that prepared the human body for fast and promoted health. Accordingly, the famous physician Avicenna recommended eating two meals a day, one taken prior to sunrise and the second taken in the evening at dusk[12]. The ancient physicians of Andalusia also believed in the importance of consuming two to three meals a day separated by 6–12 h intervals depending on the nature of the individual and their health status[12]. By the middle-ages, however, eating breakfast in Europe was seen as a sinful act, and physicians warned against eating breakfast as it was thought to be detrimental to health[13]. It was not until later in the 16th century that breakfast became recognised as an essential meal[13], and proverbs such as ‘Eat breakfast yourself, share lunch with a friend and give dinner away to your enemy’ or ‘Eat breakfast like a king, lunch like a prince and dinner like a pauper’ became prevalent.

Recent evidence obtained from both randomised controlled trials and observational studies have indeed documented the importance of breakfast consumption and its associated benefits to health[14]. Several studies have also investigated the relationship between night eating and cardiometabolic disorders, including obesity[15]. Furthermore, the way the overall energy load is distributed across the day has also been shown to result in altered physiological adaptations[16,17]. The exact reason for this is not clear. However, recent evidence has emerged suggesting that various genes involved in substrate metabolism such as dietary lipids are under direct control of the circadian rhythm dictating their metabolic fate towards oxidation or storage[18].

Such studies highlight the importance of understanding the role of circadian rhythms and chronobiology in nutrition and how these may alter the physiological status. The exact driver behind such alterations is not clear. Nonetheless, given the complex interplay between the various eating occasions and the fact that energy intake at one eating occasion is not independent of intake at previous or subsequent occasions, it is critical to consider a broader approach that encompasses the so-called circadian rhythms of eating and in which timing of energy intake is considered across the full spectrum of eating occasions.

Against, this background, the current review aimed: (1) to describe current trends in energy intake across the day in the general population worldwide and contrast differences in time-of-day of energy intake across the life-course, and different sexes, and (2) to systematically review the association between time-of-day of energy intake in relation to metabolic disease, particularly obesity.

Identifying observational studies

The present review included observational studies that used a cross-sectional or longitudinal design and which had quantitative data on energy intake at different eating occasions, wherein eating occasions were categorised into either pre-defined meal slots, self-defined or statistically defined. All published studies that used a quantified dietary assessment method (24 h recall, food records, diet history) to estimate energy intake at different eating occasions were included. We excluded qualitative studies that assessed frequency of eating occasions, or that simply reported proportions of meal consumers or skippers, as well as methodological and validation studies. Studies that looked at specific population groups (i.e. athletes) or patients were also excluded. We did not consider studies that assessed energy intake at specific eating occasions (i.e. breakfast) without reporting energy intake at other eating occasions.

Characteristics of observational studies

Overall, 1660 titles were identified using the search terms (see supplementary material), of which fifty were duplicates. An additional three titles were identified using manual searches of reference lists. Based on assessment of titles, a total of twenty-five abstracts were identified as potentially relevant. Of the latter studies, five studies were excluded because the main outcome of interest was comparing energy intake from snacks *v.* meals[19–23]. One other study focused on meal and snack patterns and daily eating frequency[24]. Overall,

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eleven full-text articles were included in the present review[25–35]. These studies are summarised in Table 1.

There was a wide variation in the dietary assessment methods, with the majority of studies using food records and 24 h recalls. Moreover, the definition of eating occasions varied widely. In most studies, eating occasions consisted of pre-defined meal slots[25,26], and in a few occasions survey members self-reported the type of eating occasion with the aid of a list containing standardised meal and snack names. Sjoberg *et al.*[35] used a diet history method alongside an interview with a dietitian. The questionnaire used as part of the diet history method had a quantitative element and was divided into sections to cover breakfast, lunch, dinner and in-between meals eating occasions. Meals were defined based on the locations and time of intake during the day, thereby taking into consideration the elements of 'when' and 'where'. Accordingly, breakfast was defined as intake in the morning before school, while lunch was considered as intake during lunch break at school and dinner as the main meal in the afternoon after schools. By contrast, Howarth *et al.*[36] assessed eating patterns based on data collected from two 24 h dietary recalls. Eating occasions were standardised using a statistical method that incorporated both self-reported definitions of eating occasions with a statistical approach incorporated a time element. For instance, two or more meals consumed within 59 min of each other were deemed to be one eating occasion[36]. Similarly, if a brunch was reported or multiple same meals (i.e. two dinners), an *a priori* criterion was used to recode these eating occasions to ensure standardisation across all survey members. One study did not specify how eating occasions were defined[28]. Eating occasions reported outside the main meals (breakfast, lunch and dinner) were labelled as snacks and combined into one category. Only one study did not combine the between-meals eating occasions to one category, which permitted evaluation of energy intake between meals and whether there were differences in energy intake at mid-morning, mid-afternoon and late-evening eating occasions[25].

In relation to obesity, 962 publications were identified using the search strategy (see supplementary material). After removing forty-four duplicates, 918 titles remained. Of these, fourteen articles were selected for further screening. An additional article was identified using manual searches. A total of ten full-text articles were found to be eligible and therefore included in the review (Table 2).

In relation to studies on obesity, various dietary assessment methods were used to assess the association between the time-of-day of energy or macronutrient intake and BMI. The number of dietary data days also varied from as few as 1–7 d. BMI was assessed as a continuous variable expressed as kg/m^2 or as *z*-scores in some studies[27,37–40], whilst in others BMI was treated as a categorical variable[41,42]. One study selected subcutaneous and visceral fat as an outcome of interest[43]. In the majority of studies, time-of-day of energy intake was assessed by dividing eating occasions into four main groups (breakfast, lunch, dinner and snacks).

Table 1. Characteristics of studies included in the review on time-of-day of energy intake (*n* 11)

First author	Publication year	Study name	Type of study	Country	*N*	Method of dietary assessment	Study population	Age range (year)	Geographic distribution
Almoosawi *et al.*	2012	MRC NSHD	Longitudinal	UK	1253	5-d estimated diet diaries	Adults	36–53	National
Vossenaar *et al.*	2009		Cross-sectional	Guatemala	449	24 h prospective diary	Schoolchildren	8–10	Local
Howarth *et al.*	2007	Continuing Survey of Food Intake	Repeated cross-sectional	USA	2685	2 × 24 h recall	Adults and elderly	20–90	Local
Stockman *et al.*	2005		Cross-sectional	Canada	180	3-d food records	Adolescents (boys)	14–18	Local
Sjoberg *et al.*	2003	Goteborg Adolescence Study	Cross-sectional	Sweden	1245	Diet history validated against 7-d estimated food record	Adolescents	15–16	Local
Winkler *et al.*	1999	MONICA	Cross-sectional	Germany	899	7-d estimated diet diaries	Adults (men)	45–64	Regional
Brombach	2001	EVA	Cross-sectional	Germany	43	3-d food records	Elderly	64–94	Local
Schlettwein-gsell *et al.*	1999	Seneca	Repeated cross-sectional	Europe	2600	Structured interview including an estimated 3 d food record	Elderly	7–75	European
Lafay *et al.*	1998	FLVS	Cross-sectional	France	2364	1-d food record for <14 years and 3-d food record for ≥14 years	Children and adults	2–70	Local
De Henauw *et al.*	1997		Cross-sectional	Belgium	1321	24 h recall	Children	6–12	Regional
Skinner *et al.*	1985		Cross-sectional	USA	225	1-d food records	Adolescents	16–18	Local

Table 2. Characteristics of studies included in the review on time-of-day of energy intake and obesity (*n* 12)

First author	Publication year	Study name	Type of study	Country	*N*	Method of dietary assessment	Study population	Age range (year)	Geographic distribution	Outcome of interest
Aljuraiban *et al.*	2015	INTERMAP	Cross-sectional	USA/UK	4680	4 × 24 h	Adults	40–59	Two-countries	BMI
Kondoh *et al.*	2014		Pooled cross-sectional study	Japan	301	3–8-day record	Adult men	21–65	National	Subcutaneous and visceral fat
Almoosawi *et al.*	2013	NSHD	Longitudinal	UK	1488	5 d food record	Adults	43–53	National	Waist circumference
Wang *et al.*	2013		Cross-sectional	USA	239	3 × 24 h	Adults	21–69	Local	BMI
Dubois *et al.*	2008		Cross-sectional	Canada	2103	24 h	Children	4	Local	Overweight
Lioret *et al.*	2008	INCA1	Cross-sectional	France	748	7-d record	Children	3–11	National	Overweight
Howarth *et al.*	2007	CSFII	Cross-sectional	USA	2685	2 × 24 h	Adults and elderly	20–90	National	BMI
Thompson *et al.*	2006		Longitudinal	USA	101	7-d record	Children	8–12	Local	BMI z-score
Maffeis *et al.*	2000		Cross-sectional	Italy	735	diet history	Children	7–11	Regional	BMI
Summerbell *et al.*	1996		Cross-sectional	UK	220	7-d weighed record	Adolescents to elderly	13–91	Local	BMI

Global trends in time-of-day of energy intake

There was a wide variation in the contribution of different eating occasions to energy intake across the studies (Table 3). Overall, four different patterns of energy distribution could be observed in these studies (Fig. 1). These patterns differed by country and geographical area (Fig. 2).

For instance, Vossenaar *et al.* assessed the distribution of energy, macro- and micronutrient intakes in a cross-sectional sample of school children in Guatemala attending third and fourth grades[26]. In this survey, lunch contributed the greatest proportion of daily energy intake, while breakfast and dinner contributed an equal proportion of daily energy intake[26]. Macronutrients followed a similar pattern of distribution as energy, whilst the distribution of micronutrients varied. Accordingly, lunch provided a greater proportion of all macronutrients, vitamin C and Zn, whereas breakfast provided more vitamins A and D, thiamine, riboflavin, folate Ca and Fe[26]. Poland followed a similar pattern of distribution with breakfast and dinner contributing approximately an equal proportion of energy intake and lunch providing the greatest contributor to energy intake over the day[30].

However in France, Switzerland, Italy and Northern Ireland, the pattern of energy distribution differed in both adults and children in that the proportion of energy intake increased progressively reaching a peak at lunch and declining thereafter. As such, lunch contributed the greatest proportion of energy intake followed by dinner and breakfast[30,33].

In Sweden, energy distribution followed a different pattern. In a cross-sectional survey conducted by Sjoberg *et al.*, dietary data were collected from 611 boys and 634 girls attending grade nine in Goteborg, Sweden[35]. Breakfast and dinner were found to contribute the greatest proportion of energy intake across the day, whilst lunch contributed the lowest proportion of energy intake over the day.

In the UK, USA, Germany, Canada, Denmark, Netherlands and Belgium, the pattern of energy distribution varied from the earlier studies. Accordingly, in the UK, the proportion of daily energy intake increased gradually across the day, with breakfast providing the lowest proportion of energy intake while dinner contributed the greatest proportion of energy intake[25]. This eating pattern was observed at different follow-ups in the MRC 1946 British Birth Cohort. This corresponds to changes in distribution of energy intake between the years 1982, 1989 and 1999, which translates to when cohort members were aged 36, 43 and 53 years. On average, dinner contributed over 40 % of daily energy intake[25]. This is was markedly higher than in any of the other surveys. Macronutrient intake also followed a pattern similar to energy distribution in this cohort[25].

Similar observations were made in the USDA Continuing Survey of Food Intake by Individuals, collected in 1994–1996, where energy intake was assessed using two 24 h food recalls. In this repeated cross-sectional survey, both younger survey members (20–59

Table 3. Proportion of energy intake at breakfast, lunch, dinner and snacks based on eligible studies (*n* 11)

Study	Publication year	Region	Country (population)	*N*	Breakfast	Lunch	Dinners	Snacks	Daily energy intake (kcal)
Almoosawi *et al*.	2012	North Europe	UK (adults (36 years))	1253	17	31	46	6	2067
	2012	North Europe	UK (adults (43 years))	1253	16	31	48	5	2167
	2012	North Europe	UK (adults (53 years))	1253	17	30	48	5	2003
Vossenaar *et al.*	2009	South America	Guatemala (boys)	217	24	31	23	21	1979
	2009	South America	Guatemala (girls)	232	23	29	23	24	1924
Howarth *et al*.	2007	North America	USA (older)	893	20	25	38	17	2391
	2007	North America	USA (younger)	1792	16	26	38	20	2005
Stockman *et al*.	2005	North America	Canada (boys)	180	18	26	34	22	2624
Sjoberg *et al*.	2003	North Europe	Sweden (boys)	611	21	16	26	37	2146
	2003	North Europe	Sweden (girls)	634	20	17	28	35	3085
Brombach	2001	Western Europe	Germany(women)	43	21	32	25	22	
Schlettwein-gsell *et al*.	1999	Eastern Europe	Poland (men)	19	28	33	27	12	2032
	1999	North Europe	Denmark (men)	101	19	25	35	21	1936
	1999	North Europe	Netherlands (men)	114	15	21	33	31	1816
	1999	North Europe	Northern Ireland (men)	–	22	32	30	16	2127
	1999	Southern Europe	Italy (men)	97	11	45	37	7	
	1999	Western Europe	France-Chateau Renault-Amboise (men)	142	18	45	30	7	
	1999	Western Europe	France-Haguenau (men)	109	19	39	30	12	2414
	1999	Western Europe	Switzerland (men)	123	19	39	33	9	2032
	1999	Eastern Europe	Poland (women)	23	30	26	25	9	1577
	1999	North Europe	Denmark (women)	101	17	24	36	23	1506
	1999	North Europe	Netherlands (women)	124	13	22	33	32	1410
	1999	North Europe	Northern Ireland (women)	–	20	33	28	19	1697
	1999	Southern Europe	Italy (women)	93	13	45	34	8	
	1999	Western Europe	France-Chateau Renault-Amboise (women)	137	17	48	29	6	
	1999	Western Europe	France-Haguenau (women)	110	20	37	30	13	1793
	1999	Western Europe	Switzerland (women)	126	18	43	28	11	1577
Lafay *et al*.	1998	Western Europe	France (>40 years)	94	16	44	34	2	1812
	1998	Western Europe	France (>40 years)	156	17	41	32	3	2166
	1998	Western Europe	France (≤4 years)	72	18	32	27	8	1514
	1998	Western Europe	France (≤4 years)	64	19	31	26	8	1503
	1998	Western Europe	France (11–14 years)	164	19	33	30	6	2155
	1998	Western Europe	France (11–14 years)	142	19	33	28	6	2446
	1998	Western Europe	France (15–18 years)	64	18	37	30	5	2160
	1998	Western Europe	France (15–18 years)	66	19	38	28	5	2787
	1998	Western Europe	France (19–30 years)	75	15	39	35	4	1795
	1998	Western Europe	France (19–30 years)	48	18	38	33	4	2650
	1998	Western Europe	France (31–40 years)	393	15	41	36	3	181
	1998	Western Europe	France (31–40 years)	322	17	40	34	3	2374
	1998	Western Europe	France (5–7 years)	168	18	32	27	7	1788
	1998	Western Europe	France (5–7 years)	168	18	33	27	7	1992
	1998	Western Europe	France (8–10 years)	165	18	33	29	7	1884
	1998	Western Europe	France (8–10 years)	203	19	33	30	6	2193
De Henauw *et al*.	1997	North Europe	Belgium (children)	1321	18	30	33	20	2006
Winkler *et al*.	1992	Western Europe	Germany (men)	899	17	29	33	21	2609
Skinner *et al*.	1985	North America	USA (boys)	114	12	25	31	30	3071
	1985	North America	USA (girls)	111	11	24	35	33	2063

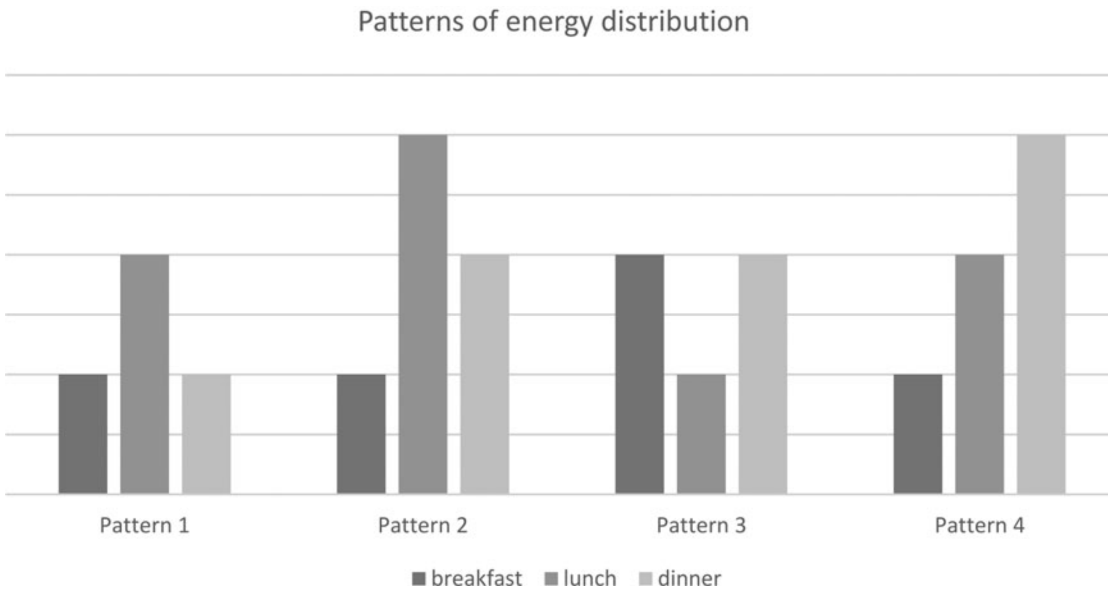

Fig. 1. Patterns of energy distribution based on eligible studies (*n* 11). Meals are ranked according to their contribution to energy intake over the day.

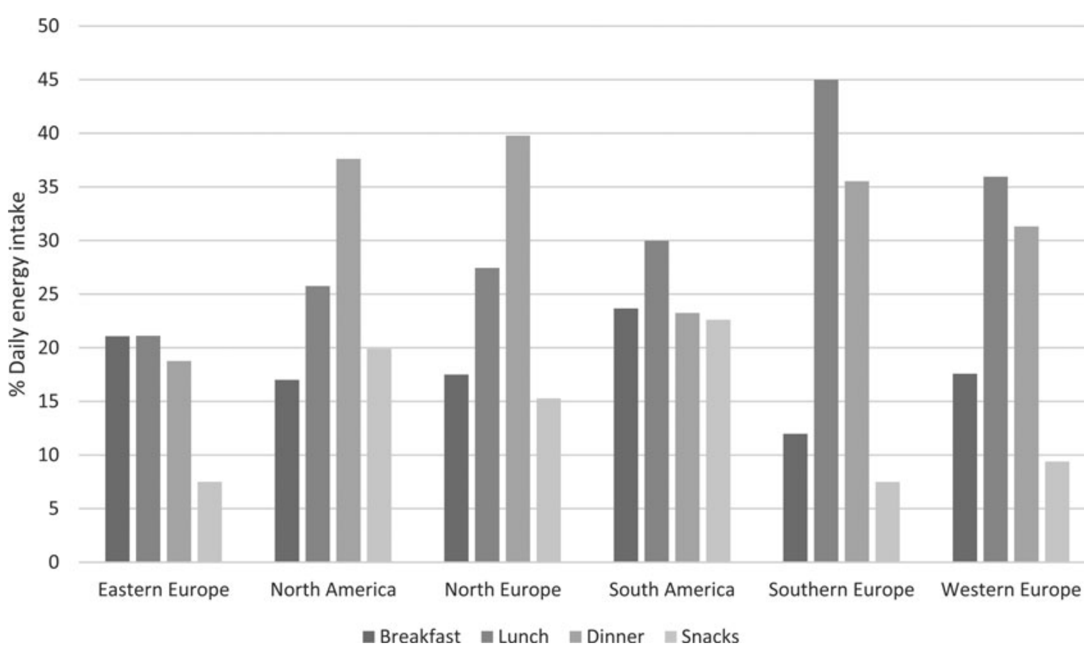

Fig. 2. Proportion of daily energy intake at breakfast, lunch, dinner and snacks according to global regions (*n* 11). Bars represent weighed means. Northern Europe region does not include data from Northern Ireland as sample size was not provided for calculation of weighed average.

years) and older survey members (60–90 years) were found to increase energy intake over the day[27].

In Canada, data were available from a small-scale study wherein 180 healthy adolescent males aged 14–18 years were recruited from local high schools and community groups. Adolescents completed a 3-d food record. Breakfast contributed 18 % of total daily energy intake (TEI), followed by lunch (26 % TEI), and dinner at 34 % (TEI)[28]. This pattern of energy distribution was consistent with the pattern observed in the UK and USA. Likewise in Germany, breakfast, lunch, and dinner contributed to TEI in the following proportions, respectively: 17, 29 and 33 %[44]. Denmark[30], Netherlands[30] and Belgium[32] followed a similar pattern with the proportion of energy intake increasing progressively through the day.

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Breakfast, snacks and meals: contribution to total energy intake

The lowest proportion of energy from breakfast was observed in US children (11 % TEI in girls, 12 % TEI in boys) and Italian adults (11 % TEI in men, 13 % TEI in women)[30]. By contrast, the proportion of TEI from breakfast was highest in Swedish boys (21 % TEI), Guatemalan children (22 % TEI in girls, 24 % TEI in boys) and Polish adults (28 % TEI in men, 30 % TEI in women; see Figs 3 and 4).

In most countries, snacks contributed a larger proportion of energy intake through the day than breakfast. Swedish adolescents and Dutch men and women[30] reported obtaining the greatest proportion of energy from snacks, whereas adults from the UK[25], France and Italy reported the lowest proportion of energy intake from snacks[30].

Secular trends in time-of-day of energy intake and differences according to age and sex

There were limited data of secular trends in time-of-day of energy intake. In the UK, data from the MRC 1946 British Birth Cohort demonstrated a trend towards increased energy intake later in the day between 1982 and 1999 corresponding to ages 36 and 53 years[25].

There were some variations in energy intake across different eating occasions amongst younger and older people. For instance, in France, the contribution of lunch and dinner to daily energy intake increased progressively from ages 4 years and below, to ages 41 and above[33]. In the USA, both younger adults and older adults obtained 38 % of their energy intake from dinner, although the younger group had a larger difference in energy intake between breakfast and dinner (15·9 % energy at breakfast *v.* 38·3 % of daily energy at dinner), compared with the older group (20·4 % energy at breakfast *v.* 38·1 % of daily energy at dinner)[27].

Few studies examined differences in time-of-day of energy intake between men and women. On average, girls obtained a lower proportion of energy intake at breakfast compared with boys in both Guatemala[26] and Sweden[35]. In Guatemala, on average, girls obtained a greater percentage of energy from snacks[35], while in Sweden, girls obtained a greater proportion of energy at dinner compared with boys[35]. In the UK, women reported obtaining a greater proportion of energy intake at breakfast than men at age 36 years[25].

There were no marked sex-differences in the proportion of energy intake from breakfast or snacks in the countries surveyed by the Seneca Study[30]. However, men from Poland reported a greater proportion of energy intake at lunch (33 % TEI) compared with Polish women (26 % TEI). Likewise, Swiss men reported a greater proportion of energy intake at dinner (33 % TEI) compared with Swiss women (28 % TEI)[30].

Time-of-day of energy intake in relation to BMI

There was a wide variation in the reported association between time-of-day of energy intake and obesity. Aljuraiban *et al.* assessed time-of-day by examining the ratio of evening-to-morning energy intake in the INTERMAP study[37]. Accordingly, morning intake was defined as mean energy intake from 06.00 hours to 11.55 hours, while evening intake was defined as mean energy intake from 18.00 hours to 23.55 hours. Times were selected based on when 98 % of the US and UK INTERMAP survey members consumed morning and evening meals. Additionally, survey members were divided into quartiles of the ratio of evening:morning energy intake (<1·0, 1·0 to <1·5, 1·5 to <2·0, ≥2·0). Based on the findings of this study, survey members with <1·0 compared with >2·0 ratio of evening:morning energy intake had lower total energy intake and dietary energy density, and better nutrient quality of individual foods and nutrient density of the overall diet, as assessed using Nutrient Rich Food Index 9.3 (NRF9.3)[45]. BMI was also found to be positively associated with evening:morning energy intake ratio, with a 2 SD difference in ratio of evening:morning energy intake being associated with a 0·2 kg/m^2 increase in BMI, after adjustment for sex, age and population sample[37]. There was a tendency for individuals to have fewer eating occasions with increasing ratio of evening:morning energy intake, although this was NS[37].

Kondoh *et al.* pooled cross-sectional data from three interventions which included a total of 301 Japanese men aged 21–65 years. Energy intake was divided into four eating occasions: breakfast, lunch, supper and between-meal intake. The association between each eating occasion and visceral and subcutaneous adiposity was assessed in multiple linear regression models after adjustment for age. Only between-meal energy intake was associated positively with subcutaneous fat. No adjustments for sociodemographic or other sample characteristics were conducted.

In a longitudinal analysis of the association between time-of-day of macronutrient intake and the metabolic syndrome, increasing carbohydrate intake at the expense of carbohydrate at age 43 years was associated with lower waist circumference at age 53 years[46].

In another small cross-sectional study, time-of-day of energy intake was assessed using three 24 h dietary recalls and stratified by time-of-day into three categories: morning (00.00–11.00 hours), midday (11.00–17.00 hours) and evening (17.00–00.00 hours)[47]. Data on time-of-day of beverage intake was not collected and, as such, energy intake from beverages was assumed to be evenly distributed across the eating occasions. The proportion of daily energy intake at morning, midday and evening was calculated, and participants were stratified into two categories; those reporting <33 % of total energy intake at morning, midday and evening, and those reporting ≥33 % of total energy intake at morning, midday and evening. In the crude analysis, higher proportion of energy intake at midday was associated with a healthy BMI. The odds of having a BMI ≥25 kg/m^2 was almost double in men reporting a higher proportion of energy intake in the evening in the overall sample, after adjustment for age, sex, race and education, TEI and physical activity. However, once only

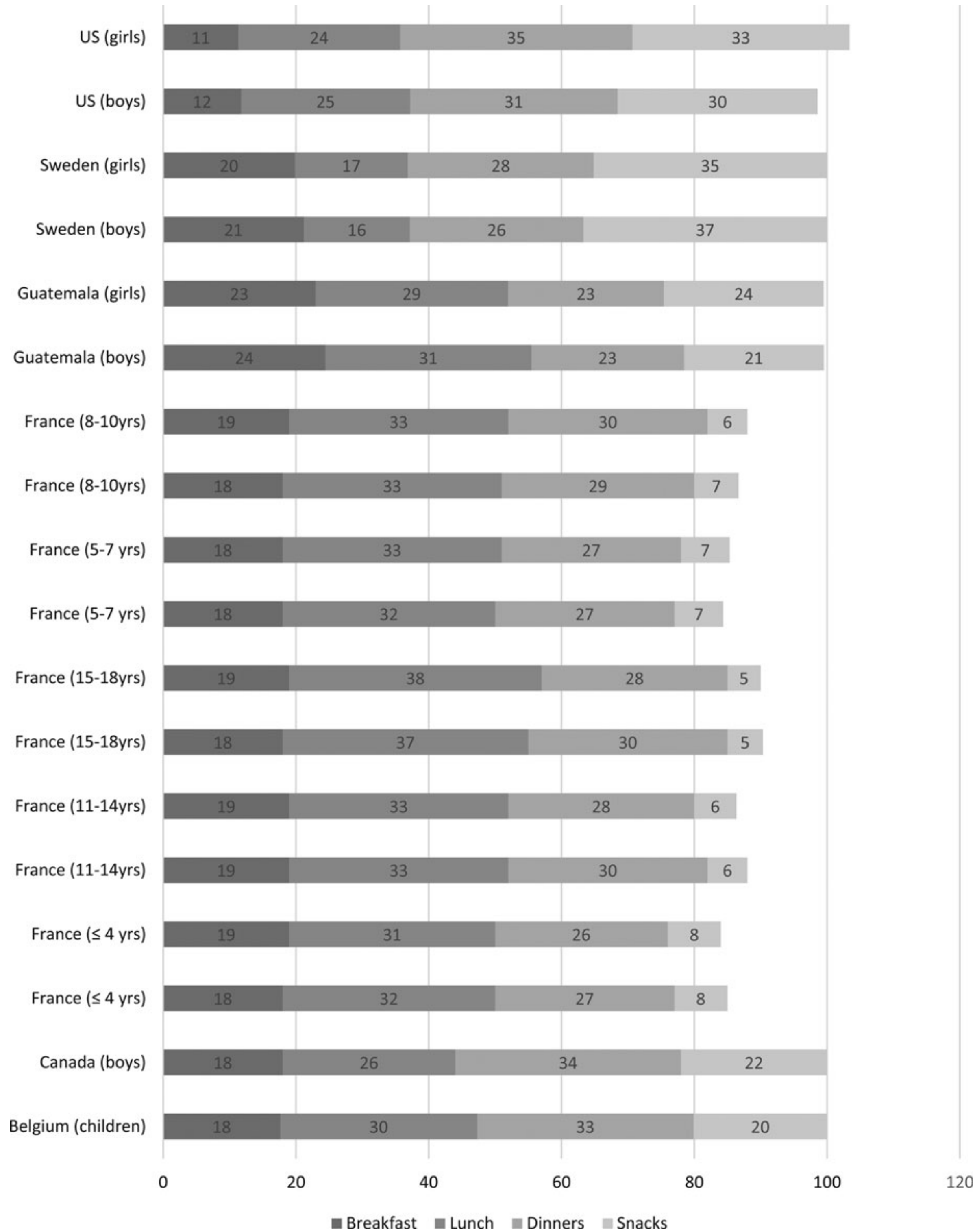

Fig. 3. Proportion of daily energy intake at breakfast, lunch, dinner and snacks in children.

men with self-reported energy intake within ±25 % of total energy expenditure as assessed by doubly-labelled water were included in the analysis, the odds of having a BMI ≥25 kg/m^2 was lower in men reporting a higher proportion of energy intake at midday but not evening.

By contrast, in a cross-sectional study investigating the association between eating behaviours (eating speed and energy intake at main meals) in pre-school children (*n* 1138; age range 3·1–6·7 years), each 418·4 kJ (100 kcal) increase in energy intake at lunch increased the likelihood of overweight by a factor of 1·445[48].

Fig. 4. Proportion of daily energy intake at breakfast, lunch, dinner and snacks in adults.

The association between breakfast skipping, BMI and time-of-day of energy intake was examined in the Longitudinal Study of Child Development in Quebec, when children were aged 44–56 months[41]. Breakfast skipping was defined as eating breakfast on fewer than 7 d/week. Differences in energy and macronutrient intake

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at breakfast, morning snack, lunch, afternoon snack, dinner, and evening snack, as assessed using a 24 h recall, were compared amongst breakfast skippers and eaters. Overall, breakfast skippers were found to have lower energy intake at breakfast and over the day, as well as higher energy intake at lunch, afternoon snack and evening snack. Breakfast skippers reported having lower energy intake from main meal and greater energy intake from between meals. Furthermore, overweight/obesity in breakfast skippers was related to a higher energy and carbohydrate intake at dinner[41].

In a representative sample of French children aged 3–11 years (*n* 748), 7-d dietary records were collected as part of a cross-sectional survey[42]. Eating occasions were categorised into four categories: breakfast, main meals (lunch and dinner) and snacks (any eating occasion other than breakfast and main meals). Overweight, defined using the International Obesity Task Force cut-points, was associated with a higher proportion of daily energy intake from main meals and snacks[42].

Howarth *et al*. compared the association between eating patterns, including time-of-day of energy intake, and BMI in younger (20–59 years, *n* 1792), and older (60–90 years, *n* 893) participants of the Continuing Survey of Food Intakes by Individuals[27]. Data were collected between 1994 and 1996. Higher BMI was associated with a higher TEI and higher intakes at all eating occasions in participants reporting plausible energy intake. The proportion of energy intake at different eating occasions was, however not assessed[27].

In a convenience sample of 101 girls selected from a longitudinal growth and development study, dietary data were collected using a 7-d food record at baseline when cohort members were aged 8–12 years and at a follow-up when the same girls where aged 11–19 years[38]. Given that participants reported atypical eating patterns dietary events were classified based on time-of-day, frequency and amount of energy intake. Using data on time-of-day, dietary events were classified as morning (06.00–10.59 hours), afternoon (11.00–16.59 hours) and evening/night (17.00–05.59 hours). After controlling for baseline BMI *z*-score, the mean percentage of daily energy intake at evening/night was positively associated with change in BMI *z*-score[38].

Maffeis found a correlation between proportion of energy intake at breakfast, dinner and night snack and percentage fat mass in children[39]. There was a significant correlation between energy intakes at different eating occasions. Proportion of daily energy intake at dinner explained 2 % of the variation in children's BMI after adjustment for sex, energy intake/BMR ratio and parental BMI.

In another small-scale study, eating patterns were assessed in 220 individuals who completed 7-d weighed dietary records[40]. In the latter study, 187 records were obtained from three independent studies, and data were reanalysed. These studies provided data on three age groups in the British population: Elderly group (*n* 88), Middle-aged group (*n* 40), Working age group (*n* 59). A fourth study of 13–14-year olds living in Croydon was carried out from which thirty-three usable diet records were collected to produce the Adolescent group. Greater energy intake at breakfast was associated with a lower BMI in the Adolescent group. In the Middle-aged group, greater energy intakes at breakfast and lower energy intakes during the evening were associated with a lower BMI. However, only the association between breakfast energy and BMI in the Adolescent group remained significant after including individuals with plausible energy intakes.

Summary of the evidence and current challenges

The present review provides a summary of published data on the time-of-day of energy intake in Northern and Southern Europe, and in North and South America. Despite the limited number of studies published in this field, data suggest that there are four patterns of energy distribution over the day. These patterns varied by country and geographical area. Although the factors contributing to such geographical differences in time-of-day of energy intake are not clear, they may potentially reflect sociocultural habits or beliefs related to eating behaviour. For instance, the fact that lunch is the most important meal of the day is characteristic of France and the Mediterranean region[49], and serves as a reflection of the French beliefs of the importance of the pleasurable and social aspects of eating[50]. Consequently, the French tend to eat together as a household more regularly and to follow a regular meal pattern of three meals daily[49]. By contrast, in central England, individual ethics and convenience drive food choices and intake, which is then translated as increased consumption of ready-prepared and take-away meals, as well as higher intake of energy-dense snack foods such as crisps[49]. Indeed, such reliance on individual ethics and convenience may potentially favour an individual pattern of consumption where people prepare and consume meals alone and eat away from home[49]. This is particularly concerning given the established association of family meals with better diet quality and meal structure[51]. The absence of the latter might explain the greater prevalence of meal skipping in England compared with France[49]. This said, although a shift towards greater energy intake at the evening meal has been reported in France in recent decades[49] due to changing working patterns[52], the destructure of French eating patterns is not yet on par with the patterns observed in England[49]. This highlights the need for further studies to determine the sociocultural and socio-economic factors that govern time-of-day of energy intake. For instance in relation to breakfast, it is now well recognised that amongst children; girls, older adolescents, children from families within the lower socio-economic groups and those living in single-parent families are more likely to skip breakfast[53].

In relation to in-between meal energy intake, evidence from the literature demonstrated that the contribution of snacks to energy intake varied from as high as 37 % of TEI in Swedish boys[35] to as low as 2–3 % of TEI in French adults[33]. In most countries, snacks provided a

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similar contribution to TEI as breakfast or more. The implications of the varying energy intake from snacks in relation to cardio-metabolic risk factors warrant investigation. However, it is important to mention that the majority of studies did not differentiate between mid-morning, mid-afternoon or late-evening eating occasions, with most studies aggregating in-between meal energy intake into one 'snack' category. This raises several challenges as the proportion of TEI at different time points might be more relevant than the total energy intake from snacks. Consistent with the latter hypothesis, it has previously been reported that consuming a small snack at night (23.00 hours) for 2 weeks, compared to a morning snack (10.00 hours), leads to a decline in 24 h fat oxidation[54].

In addition to the time-of-day of snack intake, the composition of snacks taken in-between meals might equally be important. For instance, in a study examining snacking behaviour in Scottish school children, 77 % of children reported eating biscuits, cakes and pastries; whilst 72 % ate crisps and savoury snacks; 70 % ate confectionery; and 69 % ate fruit as part of a snack[55]. In the USA, desserts, salty foods and sugar-sweetened beverages are the greatest contributors to energy intake from snacks[56]. By contrast in France, snacking is reported to be rare amongst adults, and when it does occur, it consists mainly of foods such as bread, cheese, yoghurts and fresh fruit rather than cakes, sweet biscuits or confectionery[57]. This again emphasises potential socio-cultural values related to eating behaviour.

With regard to secular trends, only one study had longitudinal data on time-of-day of energy intake. In the present study, a trend was observed towards increased energy intake later in the day between 1982 and 1999, corresponding to ages 36 and 53 years,[25]. The present study was, however, limited because it was based on data from a birth cohort. This rendered it impossible to differentiate secular trends from age trends. Differentiating secular and age trends is important to elucidate whether the recent increase in obesity prevalence is associated with a global trend towards increased energy intake later in the day, or whether it is related to life-style changes related to ageing.

Only a few studies examined differences in time-of-day of energy intake across different age groups. Accordingly, it was observed that, in France, lunch and dinner meals contribute a greater proportion of TEI in adults compared with children[33]. Similarly, in USA, there was a greater disparity between the proportion of energy intake at breakfast *v*. dinner in younger adults compared with older adults[27], which might reflect greater breakfast skipping and a larger proportion of energy intake later in the day. As discussed previously, such differences might be influenced by various socio-environmental factors. This emphasises the need for investigating the context of eating occasions, and understanding how factors such as 'with whom' and 'where' influence time-of-day of energy intake.

In the context of obesity, there were a limited number of studies investigating the association between time-of-day of energy intake and obesity. Moreover, there was a large heterogeneity in terms of the population studied, dietary assessment methods used, sample size, and choice of markers of obesity. Of the ten studies included in the second part of the present review, one study found an association between breakfast and BMI[40]. Another study reported an association between lunch time intake and BMI[48]. However, the present study only assessed energy intake at lunch and did not observe or collect data on other eating occasions. Four studies identified evening energy intake as being an important eating occasion[38,39,41,47]. Out of these four, one study reported that the association between evening intake and BMI was affected by breakfast habits wherein individuals who did not consume breakfast on all days (breakfast skippers), had higher BMI with increasing energy and carbohydrate intake in the evening[41]. Similarly, one of the studies reported that the mean percentage of daily energy intake at evening/night is associated with a longitudinal increase in BMI *z*-score in girls[38]. Likewise, Wang *et al.* found that the association between evening intake and BMI diminished after removing individuals who may have potentially mis-reported their energy intake[47]. A further two studies reported an association between energy intake between meals and subcutaneous fat and BMI, respectively[42,43]. On the balance of this evidence, it could be speculated that evening energy intake is a major risk factor for obesity. However, additional data from cross-sectional and longitudinal surveys will be required to confirm such findings. Given the heterogeneity of the studies included in the present review, it was not possible to conduct a meta-analysis of the data. Moreover, it is important in future to differentiate between mid-morning, mid-afternoon and evening snacks, as it is likely that the time-of-day of snack intake is relevant to obesity risk.

It is noteworthy that one study found that energy intake at all occasions is associated with BMI[27]. However, in the latter study, absolute energy intake at every eating occasion was assessed without adjustment for intake at other eating occasions. It is likely that the use of absolute intake rather than proportion of TEI masks the association between time-of-day of energy intake and BMI[27]. This highlights the importance of controlling energy intake at other eating occasions when investigating the relationship between time-of-day of energy intake and obesity. Indeed in a recent clinical trial investigating the effect of redistributing the TEI on weight loss, the authors reported greater weight and waist circumference loss as well as improved insulinaemia, glycaemia and TAG levels in overweight and obese women when greater energy consumption occurred in the morning compared with the evening[58]. Therefore, the timing and distribution of the TEI across the day play an important role in relation to cardio-metabolic risk factors. It has previously been reported that glucose homeostasis naturally fluctuates across the day indicating that is governed by the internal circadian system, and is thought to involve changes in insulin signalling[59]. Similarly, lipid metabolism has also been reported to be under the influence of the circadian clock. For example, plasma TAG concentrations are elevated during the biological

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night and the postprandial response following a night-time meal is amplified compared with the same meal consumed during the day[60].

Observational studies have also reported similar findings. In addition to individual eating occasions, Aljuraiban *et al.*[37] pointed towards the importance of the ratio of evening:morning energy intake. This finding is important as it suggests the need for novel approaches to examine the relationship between time-of-day of energy intake and BMI. This could be further reinforced by Dubois *et al.*[41] who suggested that evening intake affects BMI differently based on whether individuals were regular or irregular consumers of breakfast.

There was little data on how time-of-day of macronutrient intake influences BMI. To our knowledge, time-of-day of macronutrient intake is critical to obesity, given that lipid and glucose metabolism are influenced by the circadian rhythm, a topic reviewed in a recent article by Oosterman *et al*[61]. Consistent with this, a longitudinal association between carbohydrate intake at breakfast and the abdominal obesity component of the metabolic syndrome was observed in the 1946 British Birth Cohort[46]. Likewise Dubois *et al.* reported that overweight/obesity in breakfast skippers was related to a higher carbohydrate intake at dinner[41]. Collectively, findings from both randomised controlled clinical trials and longitudinal observational studies highlight the unequivocal role of the distribution of TEI across the day plays on outcomes cardiometabolic disease risk factors, including waist circumference and body weight[41].

Gaps in the literature and future research

Findings from the present review are limited by the small number of published data in time-of day of energy intake and the inconsistencies in the definition of eating patterns or the so-called circadian rhythms of energy intake, as well as obesity. Such limitations could be overcome in the future by including unpublished results from other cross-sectional surveys across the globe.

Although a number of studies investigated the distribution of energy intake across the eating occasions, there were few data as to the potential patterns of energy distribution or so-called meal patterns that could be observed in the studied populations. Indeed, in all of the earlier studies, average intake of survey members at the three main meals and snacks taken between meals was provided. However, with the exception of Winkler *et al.*[29], none of the earlier studies examined variation in energy patterns over the day nor evaluated differences in meal patterns in their population. This renders it difficult to postulate as to whether there are variations to this traditional pattern. Although outside the scope of the present review, Kerver *et al.* identified five patterns of meal and snack intake in the Third National Health and Nutrition Examination Survey[24]. Accordingly, 7·6 % of US adults reported consuming lunch, dinner and two snacks, 8·3 % consumed breakfast, lunch, dinner and no snacks, 13·1 % consumed breakfast, dinner and two snacks, 15·4 % consumed breakfast, lunch, dinner and one snack, and 31·6 % consumed breakfast, lunch, dinner and two or more snacks[24]. To date, it remains unclear as to whether there are specific patterns of energy distribution that could be more beneficial or detrimental for health. Consequently, there is a need to elucidate how these meal patterns have changed over time, and what factors influence time-of-day of energy intake. As observed in the present review, there are differences in the contribution of the main meals to energy intake across the surveys. The latter raises the question as to what meal should ideally be contributing the greatest proportion of energy intake over the day. Although, evidence exists to suggest that a greater energy intake later in the evening is detrimental to health and is associated with increased obesity, we are still far from understanding whether, in relation to metabolic health, energy should be distributed equally across the day or whether it should be distributed with a descending pattern where breakfast contributes the greatest proportion of energy, followed by lunch and dinner. Evidence form human studies appears to indicate that satiety decreases progressively over the day, potentially implicating the need to consume a greater proportion of energy earlier in the day[62]. However, recent evidence from animal models indicates that living organisms are biphasic and that, physiologically, eating two main meals a day (a bigger breakfast with a smaller dinner) but not one meal/d (breakfast only) helps control body weight and fat accumulation[63].

To date, only selected countries have recommendations on the distribution of energy over the day, whilst more dietary recommendations provide nutrient- and food-based guidelines. As such, further research is required to shape future dietary guidelines.

One main limitation of the studies included in the present review is that eating occasions were defined using various methods such as using pre-defined meal slots, self-defined meal slots and statistically defined methods. There were inconsistencies in the definition of eating patterns or the so-called circadian rhythms of eating. Several studies described eating pattern as meal regularity or frequency. In other studies, dietary patterns was synonymously used as eating patterns and vice versa[64]. This highlights the need for a consensus to be reached in the definition of eating patterns. Furthermore, there is a need to develop novel statistical methods to investigate the relationship between time-of-day of energy intake and obesity, as intake at one eating occasion is likely to be influenced by energy intake at another eating occasion. Incorporating knowledge of time of energy intake as well as time of energy intake in relation to the biological clock and time of awakening is important.

Finally, it is noteworthy that of the data presented in the present review, only a small number of studies represented nationally relevant data from on-going surveillance studies. As such, findings from the present review might not summarise current trends in time-of-day of energy intake. Future studies should address the relationship between current trends in time-of-day of energy intake and cardio-metabolic health outcomes, particularly obesity.

Conclusion

The present review provides an indication of how energy intake is distributed over the day across the globe. Evidence of the association between time-of-day of energy and obesity was limited indicating the need for larger-scale collaborations between various countries and regions in order to sum the data from existing surveys and cohorts, and guide our understanding of the role of chrono-nutrition in health.

Supplementary material

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Conflicts of Interest

None.

Authorship

S. A. and S. V. conceptualised the study and conducted the literature search. L. G. K. and G. K. P. provided scientific input and assisted with data interpretation. All authors contributed jointly to the writing of this paper.

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