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REVIEW

Vegetarian diets in children: a systematic review

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Abstract
Purpose While the prevalence of children on vegetarian diets is assumed to be on the rise in industrialized countries, there are hardly any representative data available. In general, vegetarian diets are presumed to be healthy; nevertheless, there are concerns as to whether the dietary specifications required during infancy, childhood, and adolescence can be met. Therefore, the objective of this systematic review was to evaluate studies on the dietary intake and the nutritional or health status of vegetarian infants, children, and adolescents.
Methods The database MEDLINE was used for literature search. In addition, references of reviews and expert opinions were considered. Inclusion criteria were (1) sufficient dietary information to define vegetarian type diet and (2) characteristics of nutritional or health status. Case reports and studies from non-industrialized countries were excluded.
Results 24 publications from 16 studies published from 1988 to 2013 met our criteria. Study samples covered the age range from 0 to 18 years, and median sample size was 35. Five studies did not include a control group. With regard to biomarkers, anthropometry, and dietary or nutritional intake, the outcomes were diverse. Growth and body weight were generally found within the lower reference range. The intakes of folate, vitamin C, and dietary fiber were relatively high compared to reference values and/or control groups. Low status of vitamin B_{12} was reported in one study and low status of vitamin D in two studies.
Conclusions Due to the study heterogeneity, the small samples, the bias towards upper social classes, and the scarcity of recent studies, the existing data do not allow us to draw firm conclusions on health benefits or risks of present-day vegetarian type diets on the nutritional or health status of children and adolescents in industrialized countries.

Keywords Vegetarian diet · Dietary intake · Health · Infants · Children · Adolescents

Introduction

Vegetarian-type diets, i.e., diets avoiding meat and fish, can be categorized by the food of animal origin that is still accepted into vegetarian (lacto-ovo-vegetarian, lacto-vegetarian, and ovo-vegetarian) and vegan diets (Table 1) [1]. The prevalence of people consuming a vegetarian type diet is on the rise, in particular in Europe [2, 3]. Although representative data are scarce, it can be assumed that the prevalence of infants, children, and adolescents on vegetarian-type diets is also rising. In a German nationwide health survey from 2003 to 2006, about 2.1% of the boys and 6.1% of the girls aged 14–17 years reported being on a vegetarian diet [4].

In general, studies on vegetarian and vegan adults showed multiple health benefits, such as a lower risk for obesity, cardiovascular diseases, and diabetes [5]. However, due to the restricted food selection, vegetarians and in particular vegans need to pay special attention to potential critical nutrients, i.e., protein, iron, calcium

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Table 1 Categories of vegetarian-type diets [1]

Diet	Avoided food of animal origin
Lacto-ovo-vegetarian (LOV)	Avoidance of meat, fish and products made from these
Lacto-vegetarian (LV)	Avoidance of meat, fish, eggs and products made from these
Ovo-vegetarian (OV)	Avoidance of meat, fish, milk and products made from these
Vegan (VE)	Avoidance of all food of animal origin

vitamin D, vitamin B_{12}, iodine, and n-3 fatty acids [6–9]. Since energy and nutrient requirements are higher in relation to body weight during growth, infants, children and adolescents are particular vulnerable and they are at a higher risk for nutrient inadequacies than adults.

In addition, some of these potential critical nutrients are of specific importance during youth: Dietary protein provides the amino acids required for both the synthesis of body proteins during growth and the production of other nitrogenous compounds, such as some hormones or neurotransmitters [10]. Protein quality based on amino acid pattern is lower in plant food than in food of animal origin. Iron is essential for growth and development of the central nervous system, in particular during the first year of life, because of its role in myelination, neurotransmitter function, or hippocampal dendritogenesis [11]. As a principal component of the skeleton [10], calcium is particularly important during growth. Its metabolism is regulated by vitamin D which, therefore, is also crucial for the maintenance of bone health [12]. Vitamin B12 plays a major role in human intermediary metabolism with vitamin B12 deficiency leading to clinical haematological, neurological, and psychiatric manifestations. In particular, during infancy and toddlerhood, vitamin B12 deficiency causes failure to thrive, movement disorders, and lasting developmental delays [13]. Iodine deficiency causes inadequate thyroid hormone production and hence has multiple adverse effects on growth and development, including impaired mental function and delayed physical development [14]. Long-chain polyunsaturated fatty acids (LC-PUFA) are involved in visual and cognitive development, and associations with blood pressure and immunologic response are discussed [15].

Up to now, there is no consensus between international dietary expert associations, as to whether vegetarian and vegan diets are appropriate for the young. While the American Academy of Pediatrics (AAP) and the Academy of Nutrition and Dietetics (AND) advocate appropriately planned vegetarian and vegan diets as healthful and nutritionally adequate for individuals during infancy, childhood and adolescence [16, 17], the German Nutrition Association (Deutsche Gesellschaft für Ernährung, DGE) does not recommend a vegan diet in infancy, childhood, and adolescents due to the higher risk of nutrient deficiencies [18].

To our knowledge, no contemporary systematic review on vegetarian type diets in infancy, childhood, and adolescents has been published. Therefore, the aim of the present study was to systematically review the literature on vegetarian type diets in infants, children, and adolescents from birth to 18 years to clarify the risks and the benefits on dietary intake and nutritional or health status. Since vegetarian type diets have divergent connotations in richer and poorer countries [19] with respect to socio-economic status, lifestyle, and food market, we restricted our evaluation to studies from developed countries in Europe, Northern America, and Australia/New Zealand.

Methods

Literature search strategy

For this systematic review, the database MEDLINE (via Pubmed, Greenpilot and Medpilot) was used to identify relevant studies published in English or German up until 6th November 2014. The following search string was used (*vegetarian OR vegetarian* OR vegan OR vegan**) *AND* (*infant OR infant* OR infancy OR child OR child* OR toddler OR toddler* OR adolescent OR adolescent* OR adolescence OR pregnant OR pregnancy OR breastfeeding OR breastfed*).

In addition, the search masks, Web of science, and Google scholar were searched utilizing the keywords vegetarian and child. The reference lists of the identified articles and position statements were also scanned.

Study selection

After reading title and abstract of the identified articles, duplicate references were removed and relevant studies were selected according to the following criteria.

Inclusion criteria

- Observational or comparative study design.
- Study sample age ranged from 0 to 18 years.
- Sufficient definition of the vegetarian-type diet.
- Data on dietary intake and nutritional and/or health status.

Exclusion criteria

- Case reports, reviews, position statements, guidelines, etc.
- Studies during pregnancy or in exclusively breastfed infants.
- Studies in non-industrialized countries.
- Studies in macrobiotics.

Macrobiotics generally do not consume any food of animal origin. However, the consumption of small amounts of fish and milk is allowed occasionally [20, 21]. This diet regime is promoted as part of Eastern philosophical principles of yin and yang [21]. It consists mainly of unpolished rice, pulses, and high-fiber vegetables with small additions of seaweeds, fermented foods, nuts, seeds, and fruits (mainly cooked). Vitamin D supplements are avoided [22], but small amounts of foods of animal origin (low fat fish) are allowed [23]. Since the macrobiotic diet is not a strict vegetarian type diet and food selection of plant foods is further regulated, studies on macrobiotic diets were excluded in this review.

Relevant data were extracted including information about participants´ vegetarian diet, nutritional and health status, as well as socio-economic data from full-text articles.

Results

Literature search

Having read the title and abstract, 43 of the 829 originally identified articles were found to be relevant. By scanning reference lists of these articles, 49 additional articles were identified. Full-text versions of ten publications were not available free of charge, even after contacting the authors. The 82 remaining full-text articles were checked for accordance with the inclusion criteria.

Seventeen articles from non-industrialized countries, 15 articles on pregnant vegetarians or exclusively breastfed infants, as well as 9 articles on macrobiotics were excluded. Seventeen further studies did not meet the inclusion criteria for other reasons, e.g., no sufficient information about the vegetarian diet. Finally, 24 articles from 16 study samples were included in this review (Fig. 1).

Individual study characteristics and results

Table 2 shows the main characteristics of the 24 studies (from 16 study samples) in a chronological order. In all studies, subjects of both sexes were reported to be healthy and did not take any medication. Control groups on an omnivorous diet (in 20 studies) did not differ from the vegetarian subjects regarding age, sex, and socio-economic status.

Summary of study characteristics

The included studies were published between 1981 and 2013, most of them ($n=11$) in Central Europe [24–38] and 7 in the USA [39–47]. Nine of the articles were published after 2000 [31–38, 46], and 7 of these were conducted in Poland [31, 33–38]. Ten articles were published in the 1990s [25–30, 42–45], and the remaining five in the 1980s [24, 39–41, 47]. Beside in Poland, the remaining studies were carried out in Great Britain [24, 26, 27, 32], Slovakia [28, 29], the USA [39–47], Belgium [30], and Germany [25]. The study samples cover the age range from 0 to 18 years; two [25, 32] studies only included infants and/or toddlers. Participants were recruited either from previous studies, vegetarian institutions, or through advertisements in health stores and vegetarian communities. In general, study samples were small with fewer than 100 vegetarians (Table 2), two studies examined 400–1000 participants [39, 43], and 4 studies reported data from >1000 participants [40, 42, 46, 47]. Five of these bigger samples [40, 42, 43, 46, 47] consisted of Seven-Day Adventists (SDA). In five samples with information on family characteristics, socio-economic status and/or education level were described as high, although exact data were not given [24, 26, 27, 32, 39, 42]. The studies´ design was always observational, mainly cross sectional ($n=12$) [28–31, 33–39]. The 12 prospective studies [24–27, 32, 40–47] covered observational periods of 1–2 years [25–27, 32] up to over 13 years [24]. Dietary assessment methods included food diaries or food records [25–27, 35, 37, 45], Food Frequency Questionnaires (FFQ) [28–30, 34, 38, 39, 41–44, 46], weighed records [24, 32], or interviews [26, 27, 40]. Only two studies focused on vegan diets [24, 39].

Summary of study results

Study outcomes were heterogeneous, e.g., age of menarche [40], cognition [24], blood pressure [47], or carnitine deficiency [41]. Anthropometric data of the study samples were given in 16 studies (Table 2).

Dietary intake data described food intake, total energy intake (TEI), and selected nutrients.

Biomarkers of protein metabolism [41], iron status [25–27, 38], hormones [45], lipid profile [28, 29, 35, 37], fatty acids [29], bone markers [31, 34], and micronutrient status [32–34, 36] were assessed. An overview of selected study results is displayed in Table 3.

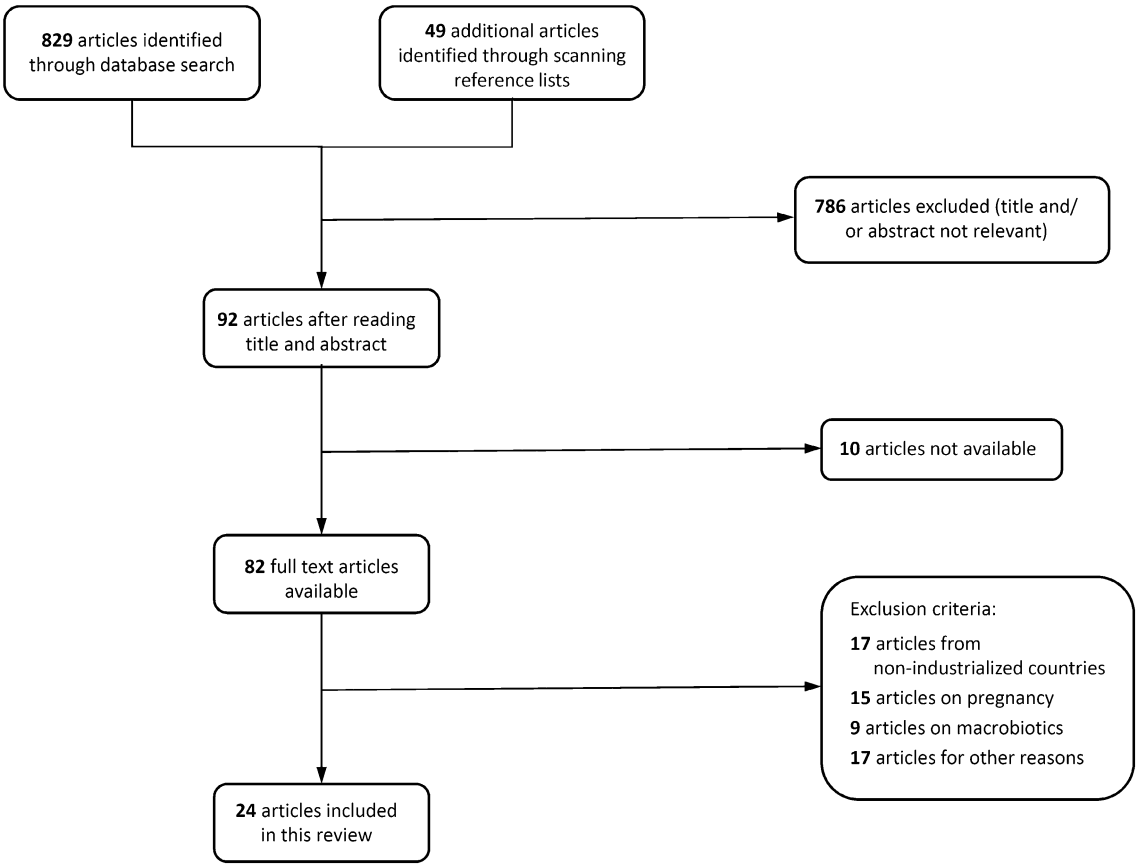

Fig. 1 Flowchart of the study selection process

Non-specified vegetarian type diets

Seven studies included children on various vegetarian-type diets as a whole sample without stratified analysis. However, from the sample characteristics reported, it could be deduced that about half of these participants were on a lacto-ovo-vegetarian diet [26–29, 31, 33–38]. Four of the seven studies including 22–32 vegetarian and 26–60 omnivorous children were from Poland, 3 of them from the same research group, published between 2003 and 2013 [31, 33–38]. Three older studies published between 1992 and 1997 came from Slovakia and Great Britain, including 26–50 vegetarians and up to 50 omnivores [26–29].

Three of the Polish studies included children aged 2–10 years of all vegetarian-type diets (lacto-ovo-vegetarian, lacto-vegetarian, ovo-vegetarian, and vegan; $n = 23–50$) as well as omnivorous control samples ($n = 18–60$). The physical development of the vegetarian samples examined by body height, body weight, or body mass index (BMI) was similar to their omnivorous counterparts and in accordance with reference values [31, 34, 35]. The intakes of macronutrients met the reference values in both groups [31, 33–36]. Results on micronutrient intakes were heterogeneous: Intake of folate in vegetarians exceeded the references (up to 200%) as well as the control group´s intake [33, 36], while vitamin D intake was found below the reference values in both groups [34, 36]. In some vegetarians, vitamin B_{12} (<1 µg/ d) and calcium intakes were below both the references and the omnivores´ intakes [33, 34, 36]. Nutrient status biomarkers showed a vitamin D deficiency in vegetarian and omnivorous children as evaluated against the cutoffs for blood concentrations of 25(OH)D, whereby vegetarians´ 25(OH)D levels were on average two-fold lower than omnivores´ concentrations [34, 36]. Mean vitamin B_{12} blood values were within the physiological range in vegetarians and omnivores [33, 36]. The bone formation markers osteocalcin, C-terminal telopeptide of type ı collagen, and bone alkaline phosphatase were 10–20% lower in vegetarians than in their omnivorous counterparts [31, 34]. By contrast, the blood lipid profile was more favourable in vegetarian participants with significantly lower total cholesterol, triglycerides, and low-density lipoprotein cholesterol [35].

The other study from Poland also included participants of all types of vegetarian diets ($n = 24$) aged between 2 and 18 years, as well as 18 omnivorous counterparts.

Table 2 Characteristics and findings of included studies

Author, year [Ref.], study location (year)	Study objective/ recruitment	Study design	Participants	Dietary data	Health data	Conclusion, *own comment*
Harris et al. 1981 [41] USA	Examination of blood pressure levels in vegetarian children Recruitment from SDA schools. Recruitment of OM from public schools in California	Prospective	3172 SDA children (6–16 years, no information about gender) Control group: 4707 OM	Not available	No significant differences between blood pressure levels of SDA and non-SDA; higher systolic blood pressure in boys >12 years than in girls; inter-ethnic comparison: higher blood pressure levels in black children at all ages	The different lifestyles of SDA and Non-SDA children do not effect blood pressure levels until the age of 16 years *Inclusion of different ethnic groups; no assessment of nutrient intake/ dietary pattern and physical development; large study sample*
Kissinger and Sachez 1987 [34] USA (1978–1981)	Examination of the association of meat consumption and the age of menarche Recruitment from SDA schools and public schools in California	Prospective	~1000 SDA and OM children (only girls, 9–15 years) No control group	Dietary assessment by interviews and 24-h recalls	Positive association between meat intake and age of menarche, negative association between meat analogues/ nuts/ grains/ beans and age of menarche	Vegetarian diet influences the age of menarche *No stratified analysis regarding nutrient intake (vegetarians and OM considered as one whole sample); no inclusion of physical development; large study sample*

Table 2 (continued)

Author, year [Ref.], study location (year)	Study objective/ recruitment	Study design	Participants	Dietary data	Health data	Conclusion, *own comment*
Sanders et al. 1988 [18] Great Britain (1968–1981)	Examination of physical development in vegan children Recruitment through previous studies on vegan diet in pregnancy	Prospective	39 vegetarian children (1–7 years, no information about gender): all vegan since birth, mean exclusive breastfeeding duration 6 month (mothers also VE); use of vit B_{12} and vit D supplements; most families with high socio-economic status No control group	Main energy and protein sources: whole grain, nuts and legumes; high consumption of fruit, vegetables, soy milk, nut milk and dried fruit, little refined sugar TEI up to 300 kcal/ d below references, protein 10% of TEI, fat 30% of TEI; Ca intake 52% of references, vit D intake below references; Fe intake 142% and vit B_{12} 280% of references (without vit B_{12} supplementation lower) Dietary assessment by 7-day weight log	Body weight, height, head and chest circumference within the normal range, weight slightly below the 50th percentile of the reference (same with boys´ height); cognitive development appropriate to age	A carefully implemented vegan diet can result in normal child development *No inclusion of biomarkers*
Lombard et al. 1989 [35] USA	Examination of the carnitine status of vegetarian children Recruitment through SDA churches in Iowa, the Hartland Institute and the VA and Weimar Institute. Recruitment of OM through Iowa City community	Cross-sectional	57 SDA children (3–17 years, 32♂, 25♀): 32 LOV, 25 VE; mean duration of eating a vegetarian diet: 10 years (LOV)/ 7 years (VE) Control group: 29 OM	Protein intake similar in SDA and OM Dietary assessment by food frequency records	Albumin and total protein blood concentrations in SDA and OM similar; significant differences of concentrations of free and total plasma carnitine between OM (mean 36/ 46 µmol/L), LOV (mean 30/ 38 µmol/L) and VE (mean 26/ 33 µmol/L); likewise with free/ total urinary carnitine: OM (mean 3/ 7 µmol/kg/d), LOV (mean 0.4/ 2 µmol/kg/d) and VE (mean 0.13/ 1.2 µmol/ kg/d); no gender effect, all measured blood concentrations were within the reference range in all groups	A vegetarian diet in childhood and adolescence might raise the risk for carnitine deficiency *No inclusion of nutrient intake (except protein) and physical development*

Table 2 (continued)

Author, year [Ref.], study location (year)	Study objective/ recruitment	Study design	Participants	Dietary data	Health data	Conclusion, *own comment*
O´Connell et al. 1989 [33] USA (1984)	Examination of physical development in vegan children Recruitment through a vegan municipality	Cross-sectional	404 vegetarian children (4 months to 10 years, no information about gender): all VE and grown up in a self-supporter municipality; 95% had been partially breastfed on average 12 months (parents were also VE); first two years of life: 83% VE, 14% LOV and 3% OM; use of vit A, vit D and vit B_{12} supplements; parents´ level of education and knowledge about vegetarian nutrition were high No control group	Main protein source: soybeans; addition of vit A, vit D and vit B_{12} to soy milk that substituted cow´s milk Assessment of dietary practice by food frequency questionnaire	Height and weight mainly within the reference range; greatest downward deviation of mean height with 2 cm in 0– 3-year-old; approach of height to the 50th percentile with increasing age	A carefully implemented vegan diet can result in normal physical child development *No inclusion of nutrient intakes and biomarkers; large study sample*
Sabaté et al. 1990 [36] USA	Examination of anthropometric data of vegetarian children and adolescents Recruitment of SDA and of control group from the study group of Harris et al. (1981) [41]	Prospective	1090 SDA children (6–17 years, 542♂, 548♀); high socio-economic status Control group: 1182 OM	Consumption of meat, dairy products, eggs, and junk food less frequently, and consumption of fruits, vegetables, starchy foods and vegetable protein products more frequently in SDA than in OM Dietary assessment by food frequency questionnaires	Mean height and weight met or were slightly above the 50th percentile of references; SDA boys 1.6 cm taller than OM boys; SDA children up to 1.27 kg lighter than OM; Mean BMI of SDA girls 0.433 lower than BMI of OM girls	A health-oriented vegetarian lifestyle during childhood and adolescence sustains adequate physical development and has preventive effects against overweight *No inclusion of nutrient intakes and biomarkers; large study sample*
Sabaté et al. 1991 [37] USA	Examination of attained height of vegetarian children and adolescents Recruitment of SDA and of control group from the study group of Harris et al. (1981) [41]	Prospective	870 SDA children (7–18 years, 427♂, 443♀): 283 LOV (meat consumption <1x/ week), 316 low meat eaters (meat consumption 1x/ week to 1x/ day), 271 medium meat intake Control group: 895 OM	92% of OM consumed meat daily; LOV consumed significantly more fruit, vegetables, starchy foods and vegetable protein products Dietary assessment by food frequency questionnaires	Heights were at or above the 50th percentile of references in all groups; LOV boys were on average 2.5 cm and LOV girls 2.0 cm taller than OM	A vegetarian diet in childhood and adolescence results in normal physical growth *No inclusion of nutrient intakes and biomarkers; large study sample*

Table 2 (continued)

Author, year [Ref.], study location (year)	Study objective/ recruitment	Study design	Participants	Dietary data	Health data	Conclusion, *own comment*
Sabaté et al. 1992 [38] USA	Examination of the effects of a vegetarian diet on height in preadolescent children Recruitment of SDA and of control group from the study group of Harris et al. (1981) [41]	Prospective	95 SDA children (11–12 years, 49♂, 446♀): all LOV, some consumed meat < 1x/ week Control group: 107 OM	See Sabaté et al. 1990 and 1991 [36, 37] Dietary assessment by food frequency questionnaires	Height of LOV girls significantly 2.5 cm lower than height of OM girls; no significant height differences between SDA and OM boys	A vegetarian diet in preadolescence might result in a different (slower) pattern of maturation *No inclusion of nutrient intakes and biomarkers*
Sievers et al. 1991 [19] Germany	Examination of Fe-status in vegetarian infants Recruitment through vegetarian families from Lüneburg. Recruitment of control group through parents from the medical sector	Prospective	13 vegetarian infants (4–12 months, 7♂, 6♀), mainly exclusively breastfed for 4 months, followed by introducing lacto-ovo-vegetarian baby food, no use of Fe-supplement Control group: 14 OM (fed meat containing baby food ≥2 meals per week)	Vegetarians: consumption of lacto-ovo-vegetarian baby food in jars (fortified with whey protein) Dietary assessment by food records	Vegetarians´ height and weight within the reference range and similar to OM; blood iron status (hb, ht, erythrocytes, erythrocyte volume, ferritin) similar to OM; Fe (15.7 µmol/L) higher and transferrin (347.0 mg/dL) lower in vegetarians with 12 months than in OM (11.3 µmol/L, 377.5 mg/dL)	A lacto-ovo-vegetarian diet in infancy does not rise the risk for Fe deficiency *No inclusion of Fe intake, but physical development; LOV´s blood transported over a long distance (analytical falsification)*
Persky et al. 1992 [39] USA (1984–1985)	Examination of hormone levels and the risk for breast cancer in vegetarian adolescent girls Recruitment from SDA schools in Chicago. Recruitment of control group from non-SDA private schools	Prospective	35 SDA (15–17 years, only girls): all LOV; no one took birth control pills, all sexually mature Control group: 40 OM	LOV consumed less calories, total fat (33.7% of total energy intake) and protein (13%) than OM (39.7%/ 15.1%); lower intake of cholesterol (203.8 vs 302.0 mg) and intake of unsaturated fat (13.6 versus 10.9 g) in LOV than in OM; iron and fiber intakes higher in LOV (11.4 mg iron per day/ 3.18 gm fiber per day) than in OM (9.5 mg/ 2.17 mg) Dietary assessment by 3-day food records	BMI (mean: 22.6 kg/(m²), age of menarche (mean: 12.3 years) similar in both groups; Mean log estradiol levels in the follicular phase of the cycle and dehydroepiandrosterone sulfate (luteal phase) significantly higher in LOV (2/ 1.88 µg/ml) than in OM (1.85/ 1.45 µg/ml); testosterone and free estradiol similar in both groups	No firm conclusion regarding hormone levels and the risk for breast cancer in vegetarian adolescents can be drawn *No inclusion of nutrient biomarkers*

Table 2 (continued)

Author, year [Ref.], study location (year)	Study objective/ recruitment	Study design	Participants	Dietary data	Health data	Conclusion, *own comment*
Nathan et al. 1996 [20] Great Britain (1992/1993)	Examination of the nutrient status in vegetarian children Recruitment in Liverpool through advertisements in schools, health food stores, the Vegetarian Society and a Hindu temple. Recruitment of control group through vegetarians´ friends	Prospective	50 vegetarian children (7–11 years, 21♂, 29♀): 23 SV (consumed fish), 27 LOV, all for at least 3 months on a vegetarian diet (most lived for ≥1 year as vegetarian); 66% of the mothers and 46% of the fathers also vegetarians; most families with high socio-economic status Control group: 50 OM	Vegetarians consumed more vegetarian ready meals, cereals rich in dietary fiber, milk products and less soft drinks than OM; fruit and vegetable intake similar in both groups Vegetarians´ daily protein (49.8 g) and TEI (7597 kJ) intake slightly below OM´s intake (59.4 g/ 8039 kJ); CHO, fat, Fe (mainly from cereals), retinol and vit C intake similar to OM; Ca (from milk), vit D (from fortified foods), thiamine, folate and vit E intake higher and vit B_{12} (247% of references) and niacin intake lower in vegetarians; reference values were met for all nutrients in both groups (except Zn, 84% of references in vegetarians) Dietary assessment by 3-day food record and interviews	Blood chol concentrations similar in both groups; hb concentrations significantly lower in vegetarians (mean 118.6 mg/L) than in OM (mean 124.1 mg/L)	Within a vegetarian diet the references for nutrient intakes can be met (for some nutrients better than by following an omnivorous diet); however, vegetarians should pay special attention to an optimal Fe absorption *No inclusion of physical development, but comprehensive food and nutrient intake*
Nathan et al. 1997 [21] Great Britain	Examination of the physical development in vegetarian children Recruitment of vegetarians and control subjects from the study group of Nathan et al. (1996) [20]	Prospective	50 vegetarian children (7–11 years, 21♂, 29♀): 27 LOV, 23 SV (consumed fish), all for at least 3 months on a vegetarian diet (most lived for ≥1 year as vegetarian); most families with high socio-economic status Control group: 50 OM	See Nathan et al. (1996)	Height and weight within the normal range; calculated final height of vegetarians with a difference of 0.47 cm on average slightly higher than OM´s final height; upper arm circumference, skin fold thicknesses (biceps and triceps) similar in both groups	A lacto-ovo-vegetarian or semi-vegetarian diet can result in appropriate physical development *Inclusion of food and nutrient intake as well as physical development*

Table 2 (continued)

Author, year [Ref.], study location (year)	Study objective/ recruitment	Study design	Participants	Dietary data	Health data	Conclusion, *own comment*
Krajcovicová-Kudlácková et al. 1997 [22] Slovakia	Examination of the effects of a vegetarian and omnivorous diet on haematological and biochemical parameters in children Recruitment through the Slovac Vegetarian Society in Bratislava. Recruitment of control group through primary schools	Cross-sectional	26 vegetarian children (11–14 years, 11♂, 15♀); LOV or LV, on a vegetarian diet for 2.8 years on average Control group: 32 OM	Assessment of dietary patterns by food frequency questionnaire, results not given	Vegetarians´ weight on average 4 kg lower than OM, height similar in both groups; blood concentrations of erythrocytes, hb (135.4 g/L in vegetarians, 142.0 g/L in OM), protein, total chol and LDL-chol within the physiological range but in vegetarians lower than in OM; hypoalbuminemia in 38% and proteinemia in 12% of vegetarians, but not in OM; HDL-chol and TG in vegetarians and OM similar; higher values of antioxidants and lower values of CD in vegetarians; 58% of the vegetarians showed Fe deficiency indicated by low serum iron (mean: 16.0 µmol/L) vs 9% in OM (mean: 22.5 µmol/L)	A vegetarian diet increases the risk of Fe and albumin deficiencies and brings health benefits through advantageously FA profile and antioxidant status *No inclusion of nutrient intake, but biomarkers and physical development*
Krajcovicová-Kudlácková et al. 1997 [23] Slovakia	Examination of the FA blood profile in vegetarian children Recruitment through the Slovak Vegetarian Society in Bratislava. Recruitment of control group through primary schools	Cross-sectional	32 vegetarian children (11–15 years, 15♂, 17♀): 15 OV, 7 VE, 10 SV (fish consumption twice a week), all on vegetarian diet for 3 years on average Control group: 19 OM	Consumption of total fat and total chol lower in vegetarians than in OM, consumption of fat from plant origin higher in vegetarians Dietary assessment by food frequency questionnaire	Vegetarians´ mean body weight and height similar to OM; lower blood concentrations of saturated FA (myristic acid 0.60% of total FA vs 0.84% in OM, palmitic acid 18.8% vs 21.86%) in vegetarians, MUFA similar in both groups; linoleic acid (35.08% vs 29.47), α linolenic acid (0.83% vs 0.67%), total PUFA (47.06% vs 42.32%) higher in vegetarians than in OM; eicosapentaenoic acid, docosahexaenoic acid and total n-3-FA highest in SE (0.75%/ 1.95%/ 3.56%) and lowest in VE (0.30%/ 0.29%/ 2.37%); n-6-FA/ n-3-FA ratio in LOV (14.71%) and in VE (19.48%) higher than in OM (13.07%) and SE (11.80%)	A vegetarian diet results in beneficial FA blood concentrations (with the exception of low n-3-FA in VE) *No inclusion of nutrient intake (except fat), but physical development*

Table 2 (continued)

Author, year [Ref.], study location (year)	Study objective/ recruitment	Study design	Participants	Dietary data	Health data	Conclusion, *own comment*
Hebbelinck et al. 1999 [24] Belgium	Examination of physical development and activity in vegetarian children and adolescents Recruitment through advertisement in health food stores and vegetarian societies. References: data of OM from a study on physical education	Cross-sectional	38 vegetarian children and adolescents (6–17 years, 19♂, 19♀); all for at least 3 years LOV Control group: 2837 OM (not self-examined)	Intake of TEI was below the reference values in vegetarians (up to 2648 kJ) Dietary assessment by 7-day food frequency questionnaire	Physical development on average within the normal range, but 10- to 17-year-old vegetarians on average 11.15 kg lighter than references; skin fold thickness in vegetarians lower than in OM; normal sexual development in vegetarians; vegetarians´ results by the standing long jump, the Sit-up-test and recovery heart rate worse than OMs´ results; vegetarians superior in endurance sports; on average LOV as fit as OM	A carefully implemented vegetarian diet can result in normal development *No inclusion of nutrient intake and biomarkers*
Ambroszkiewicz et al. 2003 [25] Poland	Examination of osteocalcin and leptin blood concentrations in vegetarian children Recruitment through the Institute of Mother and Child Warsaw	Cross-sectional	23 vegetarian children (2–10 years, 12♂, 11♀): 13 LOV, 2 LV, 8 VE Control group: 26 OM	Vegetarians´ intake of TEI, protein (16% of TEI) and CHO (55% of TEI) similar to OM´s intake; fat (27% of TEI) slightly lower and dietary fiber and PUFA intake higher than OM´s intake; intake values were within the reference range	Vegetarians´ BMI similar to OM´s BMI Osteocalcin blood concentrations in vegetarians on average 12% lower than in OM, leptin blood concentrations in vegetarians 45% lower	A vegetarian diet might affect bone health and bone formation in a negative way *No detailed examination of bone health; inclusion of physical development but not nutrient intake*

Table 2 (continued)

Author, year [Ref.], study location (year)	Study objective/ recruitment	Study design	Participants	Dietary data	Health data	Conclusion, *own comment*
Taylor et al. 2004 [26] Great Britain	Examination of the effects of meat consumption on Fe, Cu and Zn status in infants No information recruitment	Prospective	20 vegetarian children (0–24 months, 7♂, 13♀); all LOV, birthweight ≥2500 g; no use of Fe supplements, most families with high socio-economic status Control group: 178 OM	Fe intake significantly higher in vegetarians than in OM with 16, 20 and 24 months; Fe intakes in vegetarians (7.9 mg/d) in line with reference (7.8 mg/d) with 12 months, afterwards lower than reference in both groups; with 16 months Zn intake (6.12 mg/d) higher than references (5.0 mg/d) in vegetarians, at the other ages lower than references in both groups; Cu intake higher than references in both groups at any age Dietary assessment by 7-day weight log	Mean blood concentrations of hb, thrombocytes, erythrocytes, Zn-protoporphyrin, Fe and ferritin at the lower reference range in vegetarians and similar to OM; 34.1% of both groups <110 g/L hb with 4 months; mean serum Zn and Cu within the reference range in both groups; with 12 months negative correlation between number of subjects with low Fe or hb values and meat consumption	A lacto-ovo-vegetarian diet supplies infants with Fe, Cu and Zn just as an omnivorous diet *No inclusion of Fe sources, breastfeeding, physical development and macronutrients*
Ambroszkiewicz et al. 2006 [27] Poland	Examination of blood nutrient status biomarkers (homocysteine, folate, vit B_{12} and antioxidant status) in vegetarian children Recruitment through the Institute of Mother and Child Warsaw	Cross-sectional	32 vegetarian children (2–10 years, 18♂, 14♀): 21 LOV, 1 LV, 5 OV, 5 VE No control group	Mean intakes of TEI, protein, CHO, fat and vit B_{12} met the reference values (exception: vit B_{12} intakes in VE with < 1 µg/d instead of the recommended 1.0–2.0 µg/d); folate intake exceeded with 195.7 ± 78.0 µg/d the reference values of 50.0-150.0 µg/d	Blood concentrations of total chol, LDL-chol, HDL-chol, TG, homocysteine, folate, vit B_{12} and antioxidant status on average within the physiological range	A vegetarian diet supplies children sufficiently with nutrients (with the exception of low vit B_{12} intake in VE) *No inclusion of physical development*
Ambroszkiewicz et al. 2007 [28] Poland (in winter)	Examination of blood bone formation markers in vegetarian children Recruitment from the study sample of Ambroszkiewicz et al. (2006) [27]. Recruitment of control group through the Institute of Mother and Child Warsaw	Cross-sectional	50 vegetarian children (2–10 years, 27♂, 23♀): 28 LOV, 4 LV, 5 OV, 13 VE Control group: 50 OM	Intakes of TEI, protein, CHO, fat and P similar to OM´s intakes and met the reference values; Ca and vit D intakes in vegetarians below reference values and two-fold lower than in OM Dietary assessment by food frequency questionnaire	Vegetarians´ BMI on average similar to OM´s BMI; blood concentrations of Ca and P within the physiological range, vit D concentrations below the reference values in both groups (but vegetarians´ values two-fold lower than OM´s values); vegetarians´ mean blood concentrations of OC, BAP and CTX 10–20% lower than in OM	A vegetarian diet in childhood can result in poor vit D and Ca status and thus affect bone formation in a negative way *Inclusion of physical development*

Table 2 (continued)

Author, year [Ref.], study location (year)	Study objective/ recruitment	Study design	Participants	Dietary data	Health data	Conclusion, *own comment*
Ambroszkiewicz et al. 2011 [29] Poland	Examination of the relationship between adipocytokine status and anthropometric parameters in vegetarian children Recruitment through the Institute of Mother and Child Warsaw	Cross-sectional	30 vegetarian children (4–10 years, 18♂, 12♀): 15 LOV since birth, 2 LV, 9 OV, 4 VE Control group: 60 OM	Intakes of TEI and protein similar to OM´s intakes and met reference values; fat intake in vegetarians slightly lower and CHO intake higher than OM´s intakes, but within the reference range Dietary assessment by 3-day food records	Vegetarians´ height, weight, lean body mass and fat body mass within the normal range (fat body mass lower than in OM); blood concentrations of total chol, LDL-chol, HDL-chol and TG within the physiological range in both groups, blood lipid profile in vegetarians more beneficial (total chol, LDL-chol and TG values lower than in OM; leptin concentrations in vegetarians two-fold lower than in OM, adiponectin concentrations in vegetarians higher	A vegetarian diet affects blood lipids and adipocytokine concentrations in a favourable way *No inclusion of micronutrient intakes and micronutrient biomarkers; inclusion of physical development*
Laskowska-Klita et al. 2011 [30] Poland	Examination of the effects of a vegetarian diet on nutrient status in childhood Recruitment from the study sample of Ambroszkiewicz et al. (2011) [29]. Recruitment of control group through hospitals (OM temporarily under medical supervision)	Cross-sectional	32 vegetarian children (2–10 years, 18♂, 14♀): 21 LOV, 1 LV, 5 OV, 5 VE Control group: 18 OM	Mean intakes of TEI, protein, CHO, fat and PUFA met the reference values in both groups; CHO intake in vegetarians higher and fat intake lower than in OM and references. vit A intake in vegetarians 200% and folate 160% of reference values, vit E (6.6 µg/d) at the lower limit; vit D intake (1.1 µg/d) three-fold lower than reference values; vit B_{12} intake in 28% of vegetarians lower than reference	Fe, Fe binding capacity, ferritin, transferrin, vit B_{12}, vit A and vit E in vegetarians within the physiological range, homocysteine (5.79 µmol/L) and vit A blood concentration (1,25 µmol/L) similar to OM´s values; vit E and antioxidant status in vegetarians slightly lower than in OM; vit D blood levels (13.7 µg/L) in vegetarians half of the reference limit	A carefully implemented vegetarian diet in childhood results in a nutrient status according to the reference values (with the exception of vit D deficiency) *No inclusion of physical development, but of nutrient status*

Table 2 (continued)

Author, year [Ref.], study location (year)	Study objective/ recruitment	Study design	Participants	Dietary data	Health data	Conclusion, *own comment*
Gorczyca et al. 2011 [31] Poland (2006)	Examination of the blood lipid profile in vegetarian and omnivorous children with allergies Recruitment through advertisements in vegetarian magazines or followers of the Hare Krishna movement. Recruitment of control group through allergology hospital wards	Cross-sectional	24 vegetarian children (2–18 years, 6♂, 18♀): 2 VE, 10 LOV, 7 LV or OV, 5 SV; all on vegetarian diet for at least 1 year, no allergies, no use of nutritional supplements Control group: 16 OM with allergies, 18 OM without allergies	Main sources for dietary fat intake in vegetarians: olive oil, rapeseed oil, grape seed oil Dietary assessment by food frequency questionnaire	Vegetarians´ height and weight similar to OM´s; total chol, TG, HDL-chol, LDL-chol, stearic acid and oleic acid in vegetarians similar to OM´s; linoleic acid (55.9 µg/100 mL) higher and eicosapentaenoic acid (2.4 µg/100 mL) lower than in allergic OM (35.7 µg/100 mL and 6.0 µg/100 mL, resp.)	A vegetarian diet might appear as a potential therapy in allergies *Allergic children generally might have differing blood fat patterns; no inclusion of physical development or nutrient status besides fat*
Matthews et al. 2011 [40] USA	Examination of the association between the risk for overweight and a vegetarian diet in children Recruitment of vegetarians and OM through the study sample of Harris et al., 1981 [41]	Prospective	1764 SDA and OM children (879♂, 885♀, 6–18 years) No control group	Dietary data of 870 SDA and 894 OM from the study of Harris et al. 1981 (unpublished data) Dietary assessment by food frequency questionnaire	17% ($n=151$) of the boys and 20% ($n=176$) of the girls were overweight in both groups (cut-off point to identify children and adolescents as being overweight: 85th percentile of age and gender specific recommendations for BMI); negative association between nut/ vegetable intake and overweight, positive association between overweight and dairy intake, no significant association between overweight and the consumption of meat/ fish/ eggs/ fruit in both groups	High consumption of vegetables might reduce the risk for overweight, whereas high consumption of dairy products might raise the risk for overweight *No stratified analysis (vegetarians and OM considered as one whole sample); large study sample*

Table 2 (continued)

Author, year [Ref.], study location (year)	Study objective/ recruitment	Study design	Participants	Dietary data	Health data	Conclusion, *own comment*
Gorczyca et al. 2013 [32] Poland (2006)	Examination of Fe intake and Fe status in vegetarian children Recruitment through the study sample of Gorczyca et al. (2011) [31]. Recruitment of control group through hospital (routine check)	Cross-sectional	22 vegetarian children (2–18 years, 5♂, 17♀): 11 LOV, 6 LV, 5 SV; all on a vegetarian diet for at least 1 year, no use of Fe supplements; mainly parents also were vegetarians Control group: 18 OM	Intakes of TEI, protein and Fe in vegetarians similar to OM´s intakes, vit C intake (70 mg/d) higher in vegetarians than in OM (47 mg/d); Fe intake met 60 to 70% of the reference values in both groups; Vegetarians´ Fe sources: grain, mushrooms, vegetables and fruit, OM´s Fe sources: grain, meat and fish Dietary assessment by 7-day food records	Vegetarians´ height and weight similar to OM´s; higher prevalence of Fe deficiency (serum ferritin) in vegetarians (9.61 µg/L) than in OM (36.1 µg/L); negative correlation between age and Fe intake in vegetarians	A vegetarian diet in childhood rises the risk for Fe deficiency despite high vit C intakes *Inclusion of nutrient status, Fe biomarker and physical development*

BAP bone-specific alkaline phosphatase, *BMC* bone mineral content, *BMD* bone mineral density, *BMI* body mass index, *Ca* calcium, *CD* conjugated dienes, *chol* cholesterol, *CHO* carbohydrates, *CTX* C-terminal telopeptide of type I collagen, *Cu* copper, *Fe* iron, *FA* fatty acid, *hb* haemoglobin, *HDL* high density lipoprotein, *ht* hematocrit, *LDL* low density lipoprotein, *LOV* lacto-ovo-vegetarians, *LV* lacto-vegetarians, *MUFA* monounsaturated fatty acids, *OC* osteocalcin, *OM* omnivore, *OV* ovo-vegetarians, *P* phosphate, *PUFA* polyunsaturated fatty acids, *SDA* Seven Day Adventists, *SV* semi-vegetarians (vegetarians who consume fish but no meat), *TEI* total energy intake, *TG* triglycerides, *VE* vegans, *vit* vitamin, *25-OH-vit D* 25-hydroxy-vitamin D, *WHO* World Health Organization, *Zn* zinc

Vegetarians´ and omnivores´ physical development was similar and within the normal range [37, 38]. In both groups, the intakes of energy and protein met the reference values, whereas the iron intake was 60–70% of the references. In vegetarians, vitamin C intake exceeded the reference values (70 mg/ d). Blood sample analysis showed a higher prevalence of iron deficiency in vegetarians than in omnivores (mean serum ferritin: 9.61 vs 36.1 µg/L) [38]. Blood lipid levels were found within the normal range in both groups [37].

The two studies from Slovakia included adolescents of all vegetarian-type diets ($n = 16/\ 32$) aged 11–15 years as well as omnivorous controls ($n = 32/\ 19$) [28, 29]. In one of these studies, body weight and height were similar in vegetarians and in omnivores [29], while in the other study, vegetarians´ weight was 4 kg lower than omnivores´ weight [28]. There was no information about nutrient intake, but serum iron (mean: 16.0 µmol/L) and haemoglobin levels (mean: 135.4 g/L) indicated iron deficiency anaemia in 58% of the vegetarians, whereas iron deficiency was less common (9%) in omnivores (mean serum iron: 22.5 µmol/L, haemoglobin: 142.0 g/L). In vegetarians, but not in omnivores, albuminaemia (38%) and protein deficiency (12%) was found [28]. Blood levels of total cholesterol, LDL cholesterol, and saturated fatty acids were significantly lower in vegetarians [28, 29], while their levels of polyunsaturated fatty acids were higher than in omnivores (47.06 vs 42.32% of total fatty acids). Blood levels of n-3 eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) were highest in participants who consumed fish but no meat (0.75/1.95% of total fatty acids) and lowest in vegans (0.3/0.29% of total fatty acids) [29]. Taken together, these findings show more favourable blood lipid levels in the vegetarian than in the omnivorous groups.

In 50 British vegetarians (mainly lacto-ovo-vegetarians) aged 7–11 years, body weight, body height, upper arm circumference, and skinfold thicknesses showed a similar physical development as in their omnivorous controls, while the calculated final height was higher (by 0.47 cm) in vegetarians [27]. References were met for all nutrient intakes in both groups, with the exception of zinc (84% of the references in vegetarians and 94% in omnivores). The daily intakes of energy, protein, and vitamin B_{12} tended to be lower in vegetarians (7597 kJ/day, 49.8 g/day, and 247% of references) than in omnivores (8039 kJ/day, 59.4 g/day, and 329% of references). The iron status in vegetarians was lower than in omnivores (blood haemoglobin: 118.6 vs 124.1 mg/L) and 47.5% of the vegetarians (19 of 40) fell below the third percentile of a reference sample [26].

Table 3 Summary of results of the included studies

Diet type (study number)	Nutrient intake	Physical development	Nutrient/ health status
Non- specified vegetarian** ($n=7$) [20–23, 25, 27–32]	Macronutrients = ref Vit B_{12} ≤ ref Ca ≤ ref Vit D < ref Fe ≤ ref Folate, vit C > ref No nutrient supplementation	Height = ref Weight ≤ ref	Vit D* < ref Vit B_{12}*, Ca* = ref Fe-status* ≤ ref Fatty acid profile* = ref Bone formation markers* <OM
SDA ($n=4$) [34–41]	Energy, protein and fat ≤ OM Fe > OM Dietary fiber > OM No nutrient supplementation	Height ≥ ref Weight ≤ ref	Blood pressure = OM Age of menarche > OM Dehydroepiandrosterone sulfate* >OM
Lacto-ovo-vegetarian ($n=3$) [19, 24, 26]	Energy ≤ ref Infants: Fe ≤ ref, Ca, Zn = ref No nutrient supplementation	Height = ref Weight ≤ ref Infants: height and weight = ref	Fitness = OM Sexual development = ref Infants: Fe-status* = ref
Vegan ($n=2$) [18, 33]	Energy ≤ ref Dietary fiber > ref Folate > ref Ca < ref Vit D, vit B_{12} with supplementation ≥ref, without <ref Nutrient supplementation $n=2$ (Vit B_{12}, vit D, vit A)	Height ≤ ref Weight = ref	Vit D* <ref Bone formation markers* = ref BMC, BMD < ref

BMC bone mineral content, *BMD* bone mineral density, *Ca* calcium, *Fe* iron, *n* number of studies, *OM* omnivores, *ref* reference value, *vit* vitamin, *Zn* zinc

* Blood measurements

** Included study participants were on different vegetarian type diets

Lacto-ovo-vegetarian diet

Three studies from Great Britain, Belgium, and Germany, published in 2004, 1999, and 1991, respectively, included groups of 13–38 lacto-ovo-vegetarians and 14–2837 omnivores [25, 30, 32].

The German study with 13 lacto-ovo-vegetarian and 14 omnivorous infants aged 4–13 months rated the physical development in both groups as appropriate. In this study, infants were exclusively breastfed for 4 months and were subsequently given commercial ready-to-eat complementary food with or without meat while continuing breastfeeding. Iron supplements were not used. Most of the examined biomarkers of iron status (haemoglobin, erythrocytes, erythrocyte volume, serum ferritin, and haematocrit) were similar in vegetarians and controls for all ages. At the age of 12 months, vegetarians showed higher blood concentrations of iron than omnivores (15.7 vs 11.3 µmol/L), but lower values of transferrin (347.0 vs 377.5 mg/ dL) [25].

The British study examined 20 lacto-ovo-vegetarian infants and toddlers aged 0–24 months as well as 178 omnivores. This study focused on trace elements, while no information on physical development was given.

Iron supplements were not used in this study sample. The iron intake met the reference values in both groups, but after the age of 12 months, the iron intake of vegetarians exceeded the omnivores´ intakes. The intakes of zinc tended to be below the references in both groups at all ages, while copper intakes exceeded the reference values. Biomarkers of zinc and copper were within the reference range in both groups at all ages, while 34.1% of both groups pooled showed haemoglobin concentrations below the reference (110 g/L). A negative correlation between meat consumption and serum iron and haemoglobin was found in 12-month-old subjects after pooling vegetarians and omnivores [32].

In the most recent Belgium study, 38 lacto-ovo-vegetarian children and adolescents aged 6–17 years were examined. Data of 2837 omnivorous children from a study on physical education were used as references. Vegetarians´ TEI was below the references (up to 2648 kJ lower) at all ages. In general, physical and sexual development was within the normal range, but vegetarians´ skinfold thicknesses (triceps and subscapular) were lower and body weight of 10–17-year-old vegetarians was lower (−11 kg) than in omnivores. Vegetarians performed worse than omnivores on the standing long jump and the sit-up-test, and their heart recovery rate was also inferior. However, since vegetarians achieved better results in endurance sports, vegetarians were classified as fit as omnivores [30].

Seventh-day adventists

Seventh-Day Adventists (SDA) is members of an evangelical denomination in North America [47]. The church recommends a healthy lifestyle with exercise and avoidance of tobacco, alcohol, and mind-altering substances. This recommended healthy lifestyle includes a vegetarian diet defined by the avoidance of meat coupled with high intakes of legumes, whole grains, nuts, fruits, and vegetables and a source of vitamin B_{12} to promote health [48]. The degree of adherence to these dietary recommendations is heterogeneous; from previous studies, it is estimated that approximately 45% of adult SDAs are vegetarians (mostly lacto-ovo-vegetarian) [47].

Eight studies from the USA on vegetarian diets in children and adolescents were identified in the review recruiting their study participants in the SDA community and included up to 4707 omnivorous controls. Five of these studies examined the same study sample [42–44, 46, 47]. All studies considered SDA participants as one vegetarian sample without stratified analysis, even if the SDA sample included different vegetarian-type diets and low meat eaters.

The first study by Harris et al. (1981) included 3172 SDA and 4704 omnivores aged from 6 to 16 years and did not reveal significant differences in blood pressure between SDA children and the control group, despite differences in lifestyle [47].

Two further research groups included subsamples from this original sample in their studies: Four studies evaluated anthropometric data of SDA children and adolescents. In a 2-year longitudinal survey among more than 2000 children aged 6–18 years, SDA boys were 1.6 cm taller and both boys and girls were leaner (adjusted for height) than the non-SDA control group. Diet was assessed in a subgroup of 870 SDA and 895 non-SDA children by a validated FFQ.

Meat consumption of SDA children was lower than that of the control group (27.8 times per month vs 86.4 times per month), as well as dairy/egg consumption (84.6 vs 92.4), whereas consumption of fruits (120.9 vs 94.5) and starchy food (84.2 vs 77.8) was higher. The authors concluded that the health-oriented lifestyle of SDAs sustained adequate growth, but lower body weight [42]. In a further analysis of the same sample, those 32.5% of the SDA children who were categorized as vegetarians were taller than their meat-consuming classmates (2–2.5 cm), even after adjustment for food group intake, socio-economic status, and parental height [43]. The third analysis of this sample focused on preadolescents (11–12 years) and revealed a mean height of vegetarian girls that was 2 cm less than of the omnivore control group. In boys, height was similar in both dietary groups [44]. In a fourth analysis of this sample, the intake of food groups and the risk of being overweight were estimated. In particular, the intake of grains, nuts, vegetables, but also of nutrient-poor foods was associated with a lower risk for overweight, whereas the consumption of dairy was associated with an increased risk [46].

Kissinger and Sanchez [40] examined the association between age of menarche and meat consumption among approximately 1000 SDA and non-SDA girls aged 9–15 years. A subgroup of 230 girls experiencing menarche during the study period was further analysed. Intakes of food groups and nutrients were assessed by repeated 24 h recalls. As a main result, meat consumers experienced menarche 6 months earlier than vegetarians.

Lombard et al. [41] examined plasma carnitine and urinary carnitine excretion among a sample of 164 SDAs, thereof 57 children. Participants were stratified into omnivorous, lacto-ovo-vegetarian, and vegan subgroups. In children, greater differences were found between the three subgroups than in adults, with the lowest plasma and urine concentrations in the vegan group. However, the authors stated that their study did not permit conclusions regarding the risk of overt carnitine deficiency.

A comparison of plasma hormone levels in 35 vegetarian SDA girls (mean age 16.2 years) and a control group of 40 non-vegetarian girls (mean age 16.7 years) revealed increased levels of dehydroepiandrosterone sulfate in vegetarians, a hormone which is discussed to be protective against breast cancer [45].

Vegan diet

The two studies on vegan children included 39 and 404 children and were conducted in Great Britain and the USA in 1988 and 1989, respectively [24, 39].

The prospective long-term British study examined 39 vegan children starting from age 1 to 7 years, but had no control group. These children had been exclusively breastfed on average for 6 months by their vegan mothers; most children were given vitamin B_{12} and vitamin D supplements. After weaning, main protein sources were wholegrain, legumes, and soy. The physical and cognitive development was age appropriate, but body height and weight tended to be below the 50th percentile of the references.

The intakes of energy (up to 300 kcal/ d lower), calcium (52% of references), and vitamin D fell below the reference values, whereas vitamin B_{12} (280% of references, including supplements) and iron intake (142% of references) exceeded the references [24].

The US American study on vegan children (0–10 years) was carried out in a vegan self-supporter municipality. Most infants had been partially breastfed for 12 months. 83% of the children were vegan since weaning,

while the others had been on an omnivorous or lacto-ovo-vegetarian diet for the first 2 years of life. Soy was the main protein source. The soy milk substituting cow´s milk was fortified with vitamins A, D, and B_{12}. The physical development was within the reference range, but 0–3-year-old subjects were on average 2 cm smaller than the references. With increasing age, mean body weight, and height approached the 50th percentile [39].

Discussion

Our systematic review shows that the literature available is insufficient to draw up-to-date conclusions on health effects of vegetarian or vegan diets in infants, children, and adolescents in developed countries.

Growth and development

The majority of the studies indicated that body weight, body height, and other anthropometric measures of infants, children, and adolescents on vegan or vegetarian diets were in the range of or slightly below the references, or similar to omnivorous control groups [24, 25, 27–31, 34, 35, 37–39, 43, 45, 46]. In the SDA sample, boys were even taller than the control group [42]. A lower body weight [24, 28–30, 42] or fat body mass [35] compared with the control groups is in line with assumptions that vegetarian diets may be a sensible approach for the prevention of obesity in childhood [49], but the underlying mechanisms are under discussion. Four studies included in this review reported TEI below the respective references [24, 26, 30, 45], and others found TEI within the references or similar to an omnivorous control group [31, 33–36, 38]. However, it could be questioned, whether dietary survey methods used in the studies were valid enough to detect small rates of overconsumption, which result in weight gain over time.

In adults, a vegetarian or vegan diet is associated with a healthy lifestyle including high levels of physical activity. Although this has not been shown in children and adolescents yet, such higher levels of physical activity associated with vegetarian/vegan diets can contribute to lower body weight alongside diet specific contributions.

The lower body weight status can also be a result of selection bias. If data were provided, the socio-economic status of the samples in this review was high [24, 26, 27, 32, 39, 42]. It has been observed that overweight and obesity in childhood are strongly associated with the social gradient [50].

The avoidance of special foods or food groups also reduces dietary variety. Therefore, sensory specific satiety may contribute to lower TEI, in particular in vegan diets [51].

Furthermore, plant-based diets are high in vegetables, fruits, fiber, and water, resulting in a low energy density [24, 26, 52]. A food pattern analysis of the Adventist Health Study 2 showed that adult vegetarians ate more plant-based foods, including fruits, vegetables, avocados, non-fried potatoes, whole grains, soya foods, nuts and seeds than omnivores, whereas the consumption of refined grains, sweets, snack foods, added fats, and non-water beverages was lower [53]. It is supposed that such food pattern prevents weight gain [54, 55].

Vitamin D and bone health

Since the predominant food sources of vitamin D are of animal origin (fatty fish, egg yolk, dairy) [12], vegetarians and in particular vegans are at risk for a low dietary vitamin D intake. The cross-sectional Polish study examined parameters of bone health in 23 vegetarian children and reported lower osteocalcin levels [31]. In Finnish adults, intake of vitamin D was lower in vegans than in omnivores [56]. However, vitamin D status depends to a great extent on sun exposure and children and adolescents without adequate sun exposure—in particular those living in northern countries or with dark skin—are at risk for vitamin D deficiency [12]. Therefore, a supplementation of vitamin D is recommended not only for infants, but also for risk groups of children and adolescents in some European countries [12], irrespective of whether they are vegetarian or omnivorous. However, it remains to be verified, if and to which extent vegetarian or vegan families apply supplemental vitamin D. Sanders et al. (1988) [24] reported that parents of vegans were aware of the need to give supplements. Supplementation was also common in the sample of O'Connell [39], whereas in the sample of Gorczyca (2011), the use of dietary supplements per se was an exclusion criterion [37].

Iron and iodine

Iron status was one of the most examined nutrient parameters in the present review. Iron deficiency is the most common micronutrient deficiency worldwide and meat is an important source of highly available iron, and additionally promotes iron bioavailability from other sources [11]. Some studies reported a similar [26, 38] or even higher iron intake in vegetarian children and adolescents [32, 39] than in their controls. However, since bioavailability of iron from plant foods is lower than from meat [57, 58], a higher intake must not reflect a better iron status per se. In studies

presented here, iron deficiency was found in more than half of vegetarians [26, 28], and other studies indicated lower [38] or similar [32] biomarkers of iron status in vegetarian compared to omnivorous groups.

Only one study [25], although with small samples, examined the iron status of lacto-vegetarian infants getting complementary food with or without meat. Although iron requirements are high in this age group, infants fed vegetarian food showed an iron status similar to the omnivorous control group, measured by haemoglobin, haematocrit, or ferritin [25].

In contrast to iron, iodine has been neglected as a 'critical' nutrient in the studies of this review, although it is essential for optimal physical and neurological development in infants, children, and adolescents [14] and beside iodized table salt, sea-fish, and dairy are important food sources for iodine [59]. Analysis of 24 h urinary iodine excretion is a valid marker of iodine status. In a Finnish study with adults, all vegans ($n=20$), but also 91% of the non-vegetarian control group ($n=17$) had iodine concentrations in spot urines lower than the World Health Organization's limit for mild iodine deficiency (<100 µg/L urine), indicating that the risk of impaired iodine status is not specific for vegan diets but also common in the general population [56]. In the German DONALD study, higher proportions of plant-based food were associated with lower iodine excretion in children, but this association was partially mediated by salt intake [60].

Vitamin B_{12}

In vegan diets, the risk of nutrient inadequacies is supposed to be higher than in vegetarians, since the food selection is limited further. In particular vitamin B_{12} is a potential critical nutrient, because it is found originally only in meat and animal products. In both studies on vegan diets during childhood and adolescence, the use of vitamin B_{12} supplements was common and reflected by higher intake [24, 39]. The authors of the two studies concluded that "vegans can grow up to be normal children" [24] and "showed no evidence of marked abnormality" [39]. However, both studies did not examine dietary biomarkers.

There are many case reports which have repeatedly and convincingly demonstrated severe clinical symptoms of vitamin B_{12} deficiency in infants of vegan mothers [13, 61–63]. In adults, a recent systematic review showed a higher prevalence of vitamin B_{12} deficiency in vegans than in vegetarians, in particular in those vegans, who did not use supplements. The authors concluded that all vegetarians, regardless of the type of vegetarian diet, should be screened for vitamin B_{12} deficiency [6].

Macrobiotic diet

In our review, we decided to exclude studies on macrobiotic diets, since small amounts of meat and fish are allowed and food selection is further regulated [20, 21]. In a well-designed prospective study on young children in the Netherlands, such a diet resulted in severe nutrient deficiencies, e.g., reported for iron, vitamin B_{12} and vitamin D [22, 23] as well as in growth retardation and impaired bone health. As a result of scientifically based and tailored dietary advice, the macrobiotic participants in the study revised some of their recommendations and accepted fatty fish and dietary fat, at least one serving of dairy per day and a reduction of dietary fiber [22]. Remarkably, catch-up growth of the children was reported in the follow-up studies [64].

Strengths and limitations

There are some strengths and limitations of this review that have to be discussed. First, with the exception of studies on SDAs, the majority of studies consisted of only small samples, which often covered a wide age range from young childhood to adolescence. However, dietary habits may change during this period due to increasing autonomy and the influence of peers, or a tendency towards meal skipping [54]. Second, all studies enrolled volunteers, i.e., no sampling was performed, so that also in other aspects, there has most likely been selection bias (e.g., mostly healthy children, children of very health-conscious parents, etc). Third, most studies were conducted in the 1980–1990s. Since then, dietary habits in developed countries have changed, e.g., showing a trend towards nutrient fortification and supplementation [65, 66]. In addition, nowadays, the internet yields diverse information about critical nutrients and optimized dietary pattern within vegetarian and vegan diets, which were not available formerly. Fourth, outcome measures in the studies were heterogeneous (e.g., blood pressure [47], carnitine deficiency [41], physical development [27, 30, 39], or various aspects of nutritional status [32, 33]) as well as were dietary assessment methods (e.g., FFQ [28–30, 34, 38, 39, 41–44, 46]; 7-day weight log [24, 32], or food records [25–27, 35, 37, 45]). However, a majority of the studies examined blood measures as indicators of nutrient status [26, 28, 29, 31–38, 41, 45]. Fifth, half of the studies in this review were cross section and do not allow conclusions about long-term growth, development, and health during childhood and adolescence.

Within these limits, the main strength of our study is its novelty, as it summarizes the currently available heterogeneous database on vegetarian-type diets in the young.

Conclusion

This review demonstrates that the available data do not allow firm conclusions to be drawn on the benefits or risks of present-day vegetarian-type diets with respect to nutritional or health status of infants, children, and adolescents. Apart from the scarcity and heterogeneity of the studies, in general, there has in particular not yet been any long-term follow-up.

Although nutritional deficiencies are much more likely in children below 4 years than in older children and adolescents, the sample sizes of available studies do not allow stratification by age group. As a tentative conclusion, most studies presented here did not show detrimental effect of vegetarian diets in children but even pointed to beneficial health outcomes compared to omnivore diets, such as favourable lipid profile, antioxidant status, or dietary fiber intake as well as tendencies towards a lower risk of overweight. Increased health risks of vegetarian diets were particularly reported for iron status. Studies in children on vegan diets are scarce and the two studies identified in this review did not analyse biomarkers. Therefore, carefully conducted prospective studies in infants, children, and adolescents on vegan or vegetarian diets compared with omnivorous control groups are urgently needed. Dietary survey methods should consider modern food supply such as fortified foods, dietary supplements, meat, or milk surrogates (e.g., soy-based 'sausages' or vegan 'milk' beverages made from soy or grain).

In addition to the status of classical 'critical' nutrients, neglected nutrients, such as iodine, and omega-3 fatty acids should be considered by the use of suitable biomarkers; as well as sensible developmental and preventive biomarkers, e.g., for bone health and inflammation.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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