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Additional costs of lactose-reduced diets: lactose-free dairy product substitutes are a cost-effective alternative for people with lactose intolerance

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Abstract
Objective: People with lactose intolerance have to limit their consumption of lactose-containing dairy products which are a main source of Ca. In particular, for low-income people it is of interest which alternative diet form rich in Ca leads to the lowest additional costs. This study aims to calculate the additional costs of lactose-reduced diets and to show which of different options represent the most cost-effective alternative within a lactose-reduced diet.
Design: Using linear programming, food baskets with different lactose contents were calculated and were compared to a basic model, reflecting a normal diet without a limitation of lactose. By comparing the costs and the composition of the food baskets, recommendations for a lactose-reduced diet were derived.
Setting: Germany.
Participants: A consumer panel dataset representative for Germany is used for the calculations. Information on prices and nutrients is derived from the 9429 adult households without children, and information on consumed food quantities from the 3046 single households.
Results: The minimum additional food costs depend on the severity of lactose intolerance and range from 0·2 % to 6·1 % per month. It was found that the greatest adjustments due to lactose reduction could be observed within the dairy product group. In this group, with a rising lactose limit, normal milk was increasingly replaced by lactose-free milk.
Conclusion: It was shown that a lactose-reduced diet is generally associated with higher food costs. When suffering from lactose intolerance, switching to lactose-free milk seems to be the most cost-effective way to cover nutrient requirements.

Keywords
Lactose intolerance
Diet cost
Healthy diet
Linear Programming

Lactose is a kind of sugar found in milk and dairy products. Due to a lack of the lactase enzyme, which splits lactose into its components, galactose and glucose, some people cannot digest this sugar. This is known as lactose malabsorption, which affects about 68 % of the population worldwide and about 16 % of the German population(1). Between 33 % and 97 % of people with lactose malabsorption suffer from symptoms, such as abdominal pain, diarrhoea or flatulence, which are caused by the fermentation of sugar(2). People with these symptoms are considered to be lactose intolerant(2).

In Germany, people with lactose intolerance are generally recommended to eat a healthy diet low in lactose, in which milk and dairy products are only consumed to the tolerated extent(3,4). However, approximately 50 % of the Ca supply is consumed through milk and dairy products in Germany(5) and a total of 46 % of men and 55 % of women in Germany do not achieve the recommended daily Ca intake(6). Therefore, a reduction in the consumption of milk and dairy products could lead to the development of or increased Ca deficiency. The great importance of milk and dairy consumption for Ca supply is also emphasised in other European studies, for example, studies from the Netherlands and France(7,8). In addition to Ca, milk and dairy products are also important suppliers of vitamin B_{12}, B_2 and Zn. These are essential nutrients for humans, but they are not considered critical in Germany(6).

To ensure an appropriate Ca supply, people with lactose intolerance have three different options: (1) to replace milk and dairy products with lactose-free dairy-product-substitutes

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(e.g. lactose-free milk); (2) to replace them with naturally lactose-free dairy products (e.g. hard cheese); or (3) to switch to other food groups rich in Ca (e.g. mineral water, certain vegetables). However, the literature shows that lactose-free substitutes are more expensive than lactose-containing products[9–12]. If and to what extent the other options are also more expensive is unclear. However, for low-income people in particular, it is of interest if and to what extent alternative diets cause higher costs and which of the three different options are the most cost-effective. This question is of particular importance for people who receive social welfare assistance. In Germany, their budget is limited to the subsistence level calculated on the basis of a normal German diet including milk and dairy products. Potential additional costs due to lactose intolerance are not covered.

Only a few studies have focused on the additional costs of a lactose-reduced diet, and these studies only consider replacing milk and dairy products with lactose-free dairy product substitutes (option 1)[10,11,13]. A healthy food basket is created in these replacement strategies (e.g. according to references from the German Nutrition Society (DGE)) and then some or all lactose-containing dairy products are replaced with lactose-free dairy product substitutes. The option to adjust the food selection and composition by switching to naturally lactose-free dairy products (option 2) or by substituting dairy products with other foods rich in Ca (option 3) was not considered in previous studies. However, this question is highly relevant in the context of German social welfare legislation. In the German legislation, it is assumed that people suffering from lactose intolerance can switch to naturally lactose-free dairy products (e.g. hard cheese) and that this switching is not related to higher costs[14]. Against this background, the aim of this study is, firstly, to calculate the actual additional costs of a lactose-reduced diet and, secondly, to show which of the three options represents the most cost-effective alternative.

This study makes use of linear programming, which has already been used for deriving nutritional recommendations by many studies (e.g.[15,16,17,18]).The method is considered a suitable and transparent tool for formulating food-based dietary guidelines that can accommodate multiple dimensions as well as conflicting goals[19]. Using linear programming, optimal food combinations can be identified that meet a range of constraints while minimising or maximising an objective function. Applied to the present research question, the aim of this study is to identify food quantities that are consumed in Germany, meet all nutrient requirements (including Ca) and lactose restrictions and are as cost-effective as possible. In total, food baskets with five different lactose limitations were optimised and compared to a basic model, which reflects a normal diet without limitations for lactose.

In the following, the data used in this analysis and the methodological approach of linear programming are described. The results are then described and discussed. Finally, we derive some conclusions for a lactose-reduced, healthy and cost-effective diet.

Methods

Data

Linear programming model calculations rely on data to program the model's objective function and its constraints. In this study, price information on all relevant food groups, including lactose-containing and lactose-free milk and dairy products, is needed for the programming of the objective function. The programming of the constraints requires data on the nutrient contents of the relevant food groups and, in addition, on consumable food quantities including those of individual lactose-containing and lactose-free milk and dairy products.

A dataset that meets these requirements is the consumer panel dataset of the German market research institution, Gesellschaft für Konsumforschung. These data include all food purchases for consumption at home for approximately 13 000 households, which are representative for Germany. To ensure representativeness, the households in the panel are recruited based on a two-stage quota sample. In the first stage, households are recruited based on the quota for geographical areas, age, household size and nationality. In a second stage, the sample is adjusted using sampling weights, such as state, size of town, household size, age of the person in charge of the household, number of children in different age groups and nationality. The participating households document all their purchases over a period of at least 10 months a year. For this purpose, the Gesellschaft für Konsumforschung provides a barcode scanner and all articles with barcodes are scanned. For those without a printed barcode (e.g. fresh products bought at weekly markets or bakeries), the household receives a book with extra barcodes.

For our study, the Gesellschaft für Konsumforschung made available a dataset collected over the period from January to December 2011, which includes a total of 12 408 473 food purchases by 13 125 representative households. Because the data contained no details about the nutritional values of foods, we linked this information to the data. For this purpose, we used the German food composition database (Bundeslebensmittelschlüssel Version 3.01, BLS), which gives information on nutritional values for 14 814 foods available in the German market. As the BLS includes information on nutrients for foods with and without inedible kitchen waste, it was possible to link the respective form to the purchase data to obtain information on different forms of food processing (e.g. peeled or unpeeled potatoes). After linking the two datasets, there were a total of 1954 different food items in the data.

The dataset created in this way was used in this study to obtain information on the quantities of individual foods consumed as well as on prices and nutrient contents of the foods. Information on the prices and nutrient contents was derived from the 9429 adult households without children. These households were selected because the focus of this study is on the additional costs of a lactose-reduced diet for adults and children's products may have different nutrient compositions and prices. In the absence of discount prices for some lactose-free dairy-product-substitutes, average prices were calculated without distinguishing between discount and supermarket prices. Information on consumed quantities was derived from the purchasing quantities of the 3046 adult one-person households, because the focus is on adults with lactose intolerance and it is not possible to allocate the purchase quantities of multi-person households to individual household members. Information on whether the adult one-person households also prepare meals for other people or whether meals are prepared for them by other households is not available. It is assumed that this effect is balanced out across households.

Table 1 Dairy products included in the model (normal/lactose-free/soya-imitate)

Dairy products	Normal	Lactose-free	Soya-imitate
1. Hard cheese	✓		
2. Semi-hard cheese	✓		
3. Soft cheese, mozzarella	✓		
4. Proceeded cheese	✓		
5. Cream cheese, herb quark, spicy yogurt	✓		
6. Sour cream, crème fraiche*	✓	✓	
7. Sweet cream*	✓	✓	✓
8. Yogurt with additives	✓	✓	
9. Plain yogurt	✓	✓	✓
10. Quark with additives	✓	✓	
11. Plain quark	✓	✓	
12. Milk mixed beverages	✓	✓	
13. Kefir, buttermilk	✓	✓	
14. Condensed milk	✓		
15. Milk	✓	✓	✓

*According to the food pyramid, these foods are classified as fats/oils[20]. However, since these foods also contain lactose and there are some lactose-free variants, they are listed here.

Classification of the food groups

To create food baskets with tangible quantities, the 1954 foods were classified into commonly used food groups according to similarities in their nutrient profiles. Therefore, in a first step, the 1954 foods were grouped into the major food groups used in the DGE's food pyramid[20]. Compared with the DGE's food pyramid, however, two changes were introduced in this study. Firstly, the 'meat, sausage, fish and egg' group, which is summarised in one group in the German pyramid, was divided into its units, that is, 'meat, sausage', 'fish' and 'egg', to reflect the nutritional differences within the products in this group. Secondly, a further group, 'others', was introduced to include foods such as spices that are otherwise not found in the DGE's food pyramid. In total, eleven major food groups including ten food groups and one beverage group were formed and are listed in online supplementary material, Supplemental Appendix I. Foods such as ready-made products and meals, which are composed of several components, were allocated proportionally to the corresponding major food groups. Common recipes were used to determine the proportional composition of each mixed food product. Up to four main components were selected to divide the product shares into the respective food groups in the food pyramid. In a second step, each major food group was subdivided into food subgroups. A list of the 113 food subgroups as well as the average quantities consumed in each of these groups can be found in online supplementary material, Supplemental Appendix II. The food subgroups contain fifteen normal dairy products, nine lactose-free dairy product substitutes and three soya products. The replacement possibilities between these groups are shown in Table 1.

When grouping the food items, the respective consumption quantities were added up. To obtain prices and nutrients for the aggregated food groups, their quantity-weighted averages were calculated.

Description of the linear programming model

Linear programming is a scientifically recognised method that has already been used in seral international nutritional studies (e.g.[15,16,17,18]) and is receiving increasing attention from the DGE and the Federation of European Nutrition Societies as a transparent and objective tool for formulating food-based dietary guidelines[19]. The aim of this method is to minimise or maximise an objective function while meeting restrictions whereby all functions must be linear[21]. The objective function includes decision variables whose values are the model's outcomes. In this study, the outcomes are optimised food quantities resulting from a minimisation of expenditures (objective function) while meeting restrictions, which include health-, consumption- and lactose-related restrictions. In the following, the objective function, its included decision variables and the constraints are described in more detail.

Objective function and decision variables

The following equation shows the objective function z to be minimised, whereby c_j are the prices of food subgroups per gram (or millilitres for beverages) and x_j are the quantities of the food subgroups representing the decision variables in terms of weight:

$$\min z = \sum_{j=1}^{n} c_j * x_j$$

Restrictions

The restrictions are structured into two parts. On the one hand, health-related restrictions were considered to model

Table 2 Nutrition-related constraints used in the linear programming model

		Quantities/d	
	Unit	Male	Female
Energy*	kcal	2300	1800
Fat*,‖	g	≤ 77	≤ 60
SFA*,‖	g	≤ 26	≤ 20
Unsaturated fatty acids*,‖	g	≥ 51	≥ 40
PUFA*,‖	g	18–26	14–20
Cholesterol*	mg	≤ 300	≤ 300
Carbohydrates*,‖	g	≥ 288	≥ 225
Fibre*	g	≥ 30	≥ 30
Sugar†,‖	g	≤ 58	≤ 45
Protein*	g	≥ 57	≥ 48
Salt‡	g	≤ 6	≤ 6
Vitamin A*,§	mg–eq.	1–3	0·8–3
Vitamin D§,¶	µg	5–50	5–50
Vitamin E*,§	mg–eq.	14–300	12–300
Vitamin K*	µg	≥ 70	≥ 60
Vitamin B_1* (thiamine)	mg	≥ 1·2	≥ 1
Vitamin B_2* (riboflavin)	mg	≥ 1·4	≥ 1·1
Niacin*	mg–eq.	≥ 15	≥ 12
Vitamin B_6*,§	mg	1·5–25	1·2–25
Folate*	µg–eq.	≥ 300	≥ 300
Pathogenic acid*	mg	≥ 6	≥ 6
Biotin*	µg	30–60	30–60
Vitamin B_{12}*	µg	≥ 3	≥ 3
Vitamin C*	mg	≥ 110	≥ 95
Sodium*	mg	≥ 1500	≥ 1500
Chloride*	mg	≥ 2300	≥ 2300
Potassium*	mg	≥ 4000	≥ 4000
Ca*,§	mg	≥ 1000–2500	≥ 1000–2500
P*	mg	≥ 700	≥ 700
Mg*	mg	≥ 350	≥ 300
Fe*	mg	≥ 10	≥ 15
I*,§	µg	200–600	200–600
Zn*,§	mg	10–25	7–25
Cu*	mg	1–5	1–5
Mn*	mg	≥ 2	≥ 2

Sources: *Ref. [22].
†Ref. [37].
‡Ref. [38].
§Ref. [24].
‖Recommendations originally given in percentage were converted into grams considering the following assumptions: body weight: 70·7 kg (man), 60·0 kg (women); PAL: 1·4 (man and woman); energy intake: 2300 kcal (man), 1800 kcal (woman).
¶As vitamin D can be ingested through food as well as produced by the body through endogenous synthesis, a lower limit of 5 µg/d was used.

a healthy diet. On the other hand, consumption-related restrictions were included to ensure that the optimised food quantities are consumable.

Health-related restrictions. The health-related restrictions include nutrient- and food-related constraints (Tables 2 and 3). The nutrient-related constraints were intended to ensure that the modelled diet provides all macro- and micronutrients in the recommended quantities and that the diet can therefore be considered as healthy. For this purpose, the DACH reference values for adequate nutrient intake were used[22]. Recommendations were taken for a reference man and woman who were both between 25 and 50 years. Since Germans' activity levels can be classified as low and the WHO's recommendations for physical activity are mostly not achieved[23], the nutrient recommendations for a physical activity level of 1·4 were used, which corresponds to the physical activity of sedentary work with little or no strenuous leisure activities. In addition to the lower limits of nutrient recommendations, there are also upper limits for some nutrients, which should only be consumed to a limited extent[24]. This applies to vitamins A, D, E and B_6, Ca, iodine and Zn (Table 2).

Table 3 Food-related constraints used in the linear programming model

	Quantities/d	
	Male	Female
Vegetable*	≥ 400 g	≥ 400 g
Fruit*	≥ 250 g	≥ 250 g
Meat†	≤ 60·7 g	≤ 42·9 g
Fish†	≥ 25·6 g	≥ 21·4 g

Source: Ref. [25].
*According to the DGE, a portion of fruits and vegetables can occasionally be replaced by juice[39]. Assuming that occasionally means twice a week and a serving of juice comprises 200 ml, a quantity of 57·1 ml juice were considered in the model. This means that up to 57·1 g of the target quantity of fruit/vegetables can be replaced by juice. For fruit, it was also possible to replace up to 25 g of the target quantity of fruit with nuts.
†If there are recommendations with lower and higher guidelines for a food group, the values are calculated based on the energy requirements of a reference person.

In addition to the reference levels of nutrient intake, the DGE also gives some food-related recommendations (Table 3). Whereas the recommendations for vegetables and fruits are given as single values, they are given as ranges for meat and fish, whereby the upper limit is valid for athletic active men and the lower limit valid for inactive women[25]. As exact values are needed for the linear programming model, they were derived from the ranges. For an active athletic man and an inactive woman, 3000 kcal and 1800 kcal are recommended, respectively[22]. Assuming that the relationship between energy intake and the recommendations for meat and fish is linear, the values for the reference man with 2300 kcal and the reference woman with 1800 kcal are derived (Table 3).

In addition to the recommendations listed in Table 3, the DGE recommends eating three portions of milk and milk products daily, which correspond, for example, to about 200 g of milk, 200 g of yogurt and a slice of cheese (30 g)[25]. However, this recommendation could not be considered in the model because it is important to include the possibility to use alternatives to milk and dairy products if they offer a cheaper option. Other DGE requirements, such as adequate intakes of carbohydrates and fibres, and a low intake of fat and high-fat foods, are already included in the nutrient-related constraints and are therefore not additionally considered in the food-related constraints. In addition, the DGE recommends drinking 1·5 l of water a day. However, a minimum quantity for beverages was not set in the model because it was assumed that the water requirement can be covered not only by the beverage groups to be purchased but also by tap water which costs 0·2 cents/l in Germany[26] and is therefore assumed to be free of charge.

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Consumption-related restrictions. Consumption constraints were also included to ensure that the food quantities calculated by the model reflect an edible diet. Based on the representative consumer household panel of the Gesellschaft für Konsumforschung, percentiles of the different major food groups and food subgroups were calculated for the 3046 adult one-person households in the dataset. The percentiles were introduced as additional model constraints so that the individual food quantities in the optimised food basket cannot exceed or fall below these limits. To allow lactose-containing milk and dairy product groups to be substituted by their lactose-free variants, the respective food groups were combined when calculating percentiles and the common percentiles were introduced into the model.

The approach of including percentiles as consumption restrictions in a linear programming model has already been conducted in previous studies (e.g.[16,17,18,27,28,29]). To reflect usually consumed food quantities, it is desirable to choose rather narrow limits as reflected, for example, using the 25–75 % percentiles. However, when introducing these limits in addition to the nutrient and food-related constraints in the model of our study, a solution could not be found, that is, there was no possible food basket within these limits in which all nutrient- and food-related requirements could be fulfilled. This is due to the fact that 'normal' German diets are not healthy in the sense that all nutrient- and health-related requirements are met. A stepwise expansion of the limits showed that the 10–95 % percentile enabled a solution of the model so that all restrictions could be fulfilled. Therefore, the 10th and 95th percentiles were chosen as limits to represent consumable food quantities of one-person households in Germany. The consumption quantities of 10th and 95th percentiles can be found in online supplementary, Supplementary Appendix II. Even though the dataset is from 2011, it can be assumed through the use of the broad ranges (i.e. 10th–95th percentiles) that consumable food quantities in Germany are still to be found in this range.

Lactose restrictions. In this study, food baskets with different lactose limitations were optimised and compared to a basic model reflecting a normal diet without limitations on lactose. Whereas the basic model contains all above-mentioned constraints, the lactose models additionally include lactose restrictions. Various limit values are considered because the tolerance limit of lactose is different. According to the European Food Safety Authority, quantities of 20–24 g of lactose consumed over the day are well tolerated by many people with lactose intolerance. However, some people report symptoms after an intake of 12 g or in some cases even of 3–5 g of lactose[3]. To cover the range between 24 and 3 g, the additional costs of a lactose-reduced diet were calculated with daily limit values of 24, 12, 6 and 3 g in this study. In addition, a 1 g limit was considered to model a diet that is also suitable for people who are already symptomatic at amounts of 3 g.

Table 4 shows an overview of all restrictions. In total, the models include fifty-one health-related restrictions, 220 consumption-related restrictions and, with the exception of the basic model, additionally one lactose restriction in each of the five lactose models. The linear programming model considers all 272 restrictions simultaneously when compiling a food basket at minimal costs. For this purpose, those with the comparatively most favourable price–nutrient relationships are selected from the complete list of all foods. The resulting food baskets of the basic model and the five lactose models each reflect those with minimal costs under the given restrictions. A comparison of the costs of the basic model with one of each of the five lactose models shows the minimal additional costs of the different levels of a lactose-reduced diet and simultaneously reveals which food composition leads to the most cost-effective alternative.

The calculations were carried out using Excel's OpenSolver.

Results

Minimal and additional diet costs due to lactose restrictions

Table 5 shows that a normal healthy diet (basic model) generates minimal costs of 125·82 € for men and 107·32 € for women per month. With a daily limit of 24 g lactose, the monthly costs increase by 0·31 € for men and by 0·22 €

Table 4 Overview of the constraints used in the linear programming model

Basic model	Health-related restrictions	1. Recommendations regarding nutrient intake 2. Recommendations regarding food intake
	Consumption-related restrictions	3. Consumable quantities regarding major food groups (10th–95th consumption percentiles) 4. Consumable quantities regarding food subgroups (10th–95th consumption percentile)
Lactose models	Restrictions of the basic model + lactose restrictions	Different tolerance limits of lactose ≤ 24 g lactose/d ≤ 12 g lactose/d ≤ 6 g lactose/d ≤ 3 g lactose/d ≤ 1 g lactose/d

Table 5 Minimal and additional diet costs per month in the basic and lactose models

Model	Minimal diet cost in €/month		Additional diet costs in €/month		Additional diet costs in %	
	Man	Woman	Man	Woman	Man	Woman
Basic model	125·82	107·32				
Lactose models						
≤ 24 g lactose	126·13	107·53	+ 0·31	+ 0·22	+ 0·2	+ 0·2
≤ 12 g lactose	129·09	110·50	+ 3·26	+ 3·19	+ 2·6	+ 3·0
≤ 6 g lactose	130·57	111·99	+ 4·75	+ 4·67	+ 3·8	+ 4·4
≤ 3 g lactose	131·32	112·77	+ 5·50	+ 5·45	+ 4·4	+ 5·1
≤ 1 g lactose	132·45	113·87	+ 6·62	+ 6·56	+ 5·3	+ 6·1

Table 6 Quantity shares of the major food groups in the basic and lactose models

	Woman						Man					
	Basic	24 g	12 g	6 g	3 g	1 g	Basic	24 g	12 g	6 g	3 g	1 g
Quantity shares of food and beverages in %												
Food	93·8	91·9	91·8	91·7	90·2	93·8	73·9	68·5	69·1	69·1	69·0	71·9
Beverages	6·2	8·1	8·2	8·3	9·8	6·2	26·1	31·5	30·9	30·9	31·0	28·1
Quantity shares within food groups in %												
Milk/dairy products	30·0	28·7	28·7	28·6	27·4	29·7	29·4	25·5	25·6	25·6	25·5	25·4
Cereal products/potatoes	22·2	22·7	22·7	22·7	23·1	22·3	23·3	25·4	25·4	25·4	25·3	25·9
Vegetable*	23·3	23·7	23·7	23·6	24·0	23·3	22·3	23·1	23·1	23·1	23·0	22·7
Fruit*	14·6	14·8	14·8	14·8	15·0	14·6	13·9	14·5	14·4	14·4	14·4	14·2
Meat, sausage	0·9	0·9	0·9	0·9	0·9	0·9	0·8	0·9	0·9	0·9	0·9	0·8
Fish	2·2	2·2	2·2	2·2	2·2	2·1	1·8	1·9	2·0	2·0	1·8	2·0
Egg	3·0	3·1	3·2	3·2	3·2	3·2	2·8	2·7	2·4	2·4	3·1	3·0
Fat/oil	2·2	2·3	2·4	2·5	2·5	2·5	3·4	3·9	4·0	4·1	4·0	3·6
Sweets/snacks	1·4	1·3	1·3	1·3	1·4	1·2	1·6	1·7	1·7	1·7	1·7	1·7
Others	0·2	0·2	0·2	0·2	0·2	0·2	0·5	0·5	0·5	0·5	0·5	0·5
Quantity shares within beverage groups in %												
Mineral water	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0
Coffee	0·0	60·8	54·7	51·8	73·8	100·0	35·3	23·8	20·9	21·1	21·7	5·3
Tea	100·0	39·2	45·3	48·2	26·2	0·0	0·0	24·6	26·2	26·1	25·8	35·1
Soft drinks	0·0	0·0	0·0	0·0	0·0	0·0	64·7	51·6	52·9	52·8	52·4	59·6
Juice†	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0	0·0

*Fruit or vegetable juice counts as fruit or vegetable up to an amount of 57·1 g/d.
†Fruit or vegetable juice is counted as juice only when it exceeds 57·1 g/day.

for women. In contrast, with pronounced lactose intolerance and a daily limit of 1 g lactose, the minimal additional costs increase to 6·62 € for men and 6·56 € for women per month. Expressed as a percentage, the food basket with a daily limit of 1 g lactose results in a cost increase by 5·3 and 6·1 % for men and women, respectively, compared to the basic model. Overall, from these results, it can be determined that there are additional costs for a lactose-reduced diet and that the amount of the additional costs increases with an increased reduction of lactose.

Changes in the major food group compositions due to lactose restrictions

Table 6 shows the percentage composition of the major food groups in the lactose models compared with the basic model. In the basic model, food comprises a quantity share of 93·8 and 73·9 % in women and men, respectively, whereas beverages account for a share of 6·2 and 26·1 % in women and men, respectively. The small percentage of beverages particularly for women results from the fact that only the lower limit in the form of the 10th percentile but not the recommended minimum of 1·5 l/d was set in the model. The latter was neglected because the water requirement can also be met by tap water, which costs 0·2 cents/l in Germany[26] and is therefore assumed to be free of charge. The lower part of Table 6, where the percentage composition within the beverage groups is depicted, shows that the beverage consumption in the women's models is composed of tea and coffee, whereas the men's models also include soft drinks. Mineral water is not represented in any of the models.

The changes in the composition within the major food groups due to lactose restrictions are shown in the middle part of Table 6 and also graphically in Fig. 1. Figure 1(a) and (c) shows that milk and dairy products consistently

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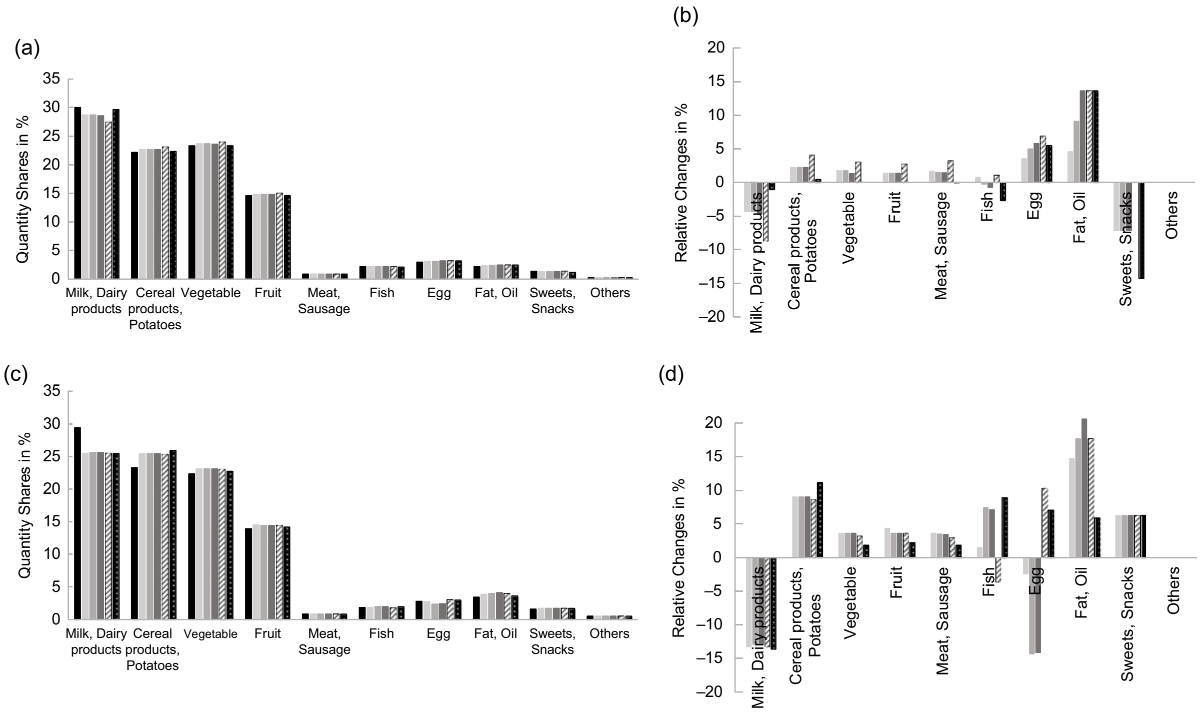

Fig. 1 Changes of the composition of the major food groups in the lactose models in comparison with the basic model. ■, basic; ■, 24 g-lactose; ■, 12 g-lactose; ■, 6 g-lactose; ▨, 3 g-lactose; ▩, 1 g-lactose

cover the highest proportions in both the basic model and all lactose models with shares between 25·4 and 30·0 % (the only exception is the male 1 g lactose model, where the cereals/potatoes group is slightly higher than the dairy products group). Whereas in women, the vegetables group is in the second place while cereals/potatoes are in the third place, but it is the other way around in men. All other food groups have the same order among men and women.

Figure 1(b) and (d) shows which proportions of the major food groups are changing the most in relative terms. With the introduction of lactose restrictions, decreasing proportions of milk and dairy products can be observed. This effect is slightly more noticeable in the models of men than in those of women. Although the quantity of milk and dairy products decreased by introducing the lactose constraints, the total quantity of milk and dairy products still constitutes the largest food group. The decreasing proportions of milk and dairy products are replaced by an increase in the proportions of the other food groups. Exceptions are the ‘Others’ food group, which remains unchanged, and the ‘Sweet Snacks’ group among women, where the shares are decreasing. Furthermore, no clear trends can be identified for the ‘Fish’ group and for men additionally for the ‘Egg’ food group. It is evident that the ‘Fat and Oil’ group is increasing relatively strongly. Obviously, the fat contained in dairy products is replaced by this group in particular. Especially for men, comparatively high increases in cereal products and potatoes can also be observed.

Changes in the milk and dairy product group composition due to lactose restrictions

The quantities of individual milk and dairy products in the basic and lactose models are shown in the upper part of Table 7. Interestingly, with a value of 440·8 g/d, the total quantity of milk (regular milk plus lactose-free milk) remains the same in all models for both men and women. As the lactose limit is tightened, however, an increasing proportion of regular milk is replaced by lactose-free milk. Thus, in the 1 g- and 3 g-lactose models, the regular milk was completely substituted by its lactose-free variant. Further changes can be observed for plain quark, kefir and buttermilk, condensed milk and dairy products as an ingredient. In men, these products are only included in the basic model but are completely substituted by other products in the lactose models. In women, the lactose-containing kefir and buttermilk are replaced by its actose-free variant in the 1 g-lactose model. Furthermore, lactose-free milk mixed beverages are additionally included in this model. The total quantity of milk and dairy products, although it is initially decreasing when a lactose limitation is introduced, noticeably increases again with strict lactose limitations. In women, it even nearly reaches the quantity of the basic model.

The quantity shares of products subdivided into lactose-containing and its lactose-free variants are shown in the bottom part of Table 7. In the basic models for both sexes, normal dairy products are mainly represented with quantity shares of just over 95 %. With an increasing limitation of the lactose contents, the shares of lactose-free dairy product

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Table 7 Quantities (g/d) and quantity shares (%) of milk and dairy products in the basic and lactose models*

	Man						Woman					
	Basic	24 g	12 g	6 g	3 g	1 g	Basic	24 g	12 g	6 g	3 g	1 g
Quantities in g/d												
Hard cheese	–	–	–	–	–	4·0	1·6	3·5	3·7	3·9	4·6	3·4
Semi-hard cheese	0·4	0·4	0·4	0·4	0·4	0·4	0·4	0·4	0·4	0·4	0·4	0·4
Sweet cream (soya)	26·3	26·3	26·3	26·3	26·3	26·3	26·3	26·3	26·3	26·3	26·3	26·3
Plain quark	41·1	–	–	–	–	–	–	–	–	–	–	–
Milk (lactose-containing)	440·8	440·8	190·3	61·1	–	–	440·8	440·1	184·8	57·2	–	–
Milk (lactose-free)	–	–	250·4	379·7	440·8	440·8	–	0·7	256·0	383·6	440·8	440·8
Milk mixed beverages (lactose-free)	–	–	–	–	–	–	–	–	–	–	–	26·3
Kefir, buttermilk (lactose-containing)	37·8	–	–	–	–	–	37·8	37·8	37·8	37·8	8·9	–
Kefir, buttermilk (lactose-free)	–	–	–	–	–	–	–	–	–	–	–	37·8
Condensed milk	7·1	–	–	–	–	–	32·8	–	–	–	–	–
Dairy products as an ingredient in ready products/meals	0·4	–	–	–	–	–	1·7	–	–	–	–	–
Total quantity	554·0	467·5	467·5	467·5	467·5	471·5	541·5	508·8	509·1	509·2	481·0	535·0
Quantity shares in %												
Lactose-containing dairy products	95·3	94·4	40·8	13·2	0·1	0·9	95·1	94·7	44·5	19·5	2·9	0·7
Lactose-free dairy product substitutes	0·0	0·0	53·6	81·2	94·3	93·5	0·0	0·1	50·3	75·3	91·6	94·4
Soya products	4·7	5·6	5·6	5·6	5·6	5·6	4·9	5·2	5·2	5·2	5·5	4·9

*In the models eleven of the twenty-seven dairy products had quantities greater than zero. The dairy products with zero values are not shown here.

substitutes increase gradually; thus, in the 1 g-lactose model, dairy product substitutes account for 93·5 and 94·4 % in men and women, respectively. In contrast, soya products play only a limited role when lactose limitations increase.

Discussion

Changes in food composition in a lactose-reduced diet

In general, milk and dairy products cover the largest shares in the basic model and also in the lactose models. Thus, they represent an important food group when fulfilling nutrient requirements at minimal costs. With a proportion of 25·4 and 29·7 % in the male and female 1 g-lactose models, the proportion is even higher than that recommended in Germany. On the basis of menu plans that meet all nutrient requirements, the German Nutrition Society (DGE) developed a nutrition circle showing the quantity proportions of six main food groups that should be consumed as part of a healthy diet. According to this nutrition circle, milk and dairy products should make up 18 % of the total amount of food consumed[30]. An explanation for the high proportion of milk and dairy products in the optimised food baskets could be that especially products with a good relationship of nutritional quality and price are selected by the model[17]. Already other studies have shown that milk and dairy products are one of the most cost-effective suppliers of Ca, riboflavin and vitamin B_{12}[31] and within this group especially, milk has a good nutrient–price ratio[17]. The comparatively high cost-effectiveness of milk could be the reason why the group of dairy products mainly consists of milk while other dairy products such as cheese, yogurt and quark are restricted due to their higher costs. Since milk contains significantly less Ca per 100 g than, for example, cheese, comparatively large amounts of milk must be consumed to cover the Ca requirement. This can explain the high weight proportion of dairy products in the food baskets.

Besides replacing regular milk and dairy products with their lactose-free variants, replacements with other food groups could also be observed when introducing lactose restrictions. However, the restructuring of the food baskets is relatively small and does not result in fundamental changes. Thus, milk and dairy products still cover the largest quantities in the food baskets. Switching to other food groups appears to be associated with only a limited cost advantage. The largest displacements could be observed within the group of milk and dairy products. Hence, it was found that normal milk is mainly substituted by lactose-free milk in the lactose models. From this finding, it can be concluded that the use of lactose-free substitutes, especially lactose-free milk, seems to be the cheapest alternative despite the higher price of the lactose-free products. Therefore, these products can be recommended within a lactose-reduced and low-cost diet.

Mineral water is generally considered to be a Ca-rich food with a high bioavailability[32]. However, mineral water was not selected in the lactose models; therefore, contrary to expectations, it was not used as an alternative to lactose-containing dairy products. This can be attributed to the fact that milk and even lactose-free milk is a cheaper source of Ca. Whereas regular milk has a ratio of 18·86 mg Ca per cent and lactose-free milk has a ratio of 11·98 mg Ca per cent, it is only 1·88 mg Ca per cent for mineral water. In this context, it should be noted that the Ca content of mineral waters can vary considerably. In the nutrient database (BLS), used in this study, mineral water has a Ca content of 50 mg/l. However, there are also Ca-rich mineral waters with contents above 150 mg/l. In this case, the mineral water has a ratio of 5·64 mg Ca per cent, which reveals that milk and lactose-free milk would still be the cheaper Ca suppliers. In addition, milk provides a greater variety of other nutrients than mineral water that are important for the whole body and a healthy skeleton[33].

Additional cost of a lactose-reduced diet

It has been shown that a lactose-reduced healthy diet is associated with higher costs and that the level of additional costs depends on the severity of lactose intolerance. This association was also found in previous studies. A study that statistically analysed actual expenditures on food showed that people with lactose intolerance spend on average 13·19 €/month more on food than people without lactose intolerance[34]. These results are based on the same dataset used in this study and show how high the additional expenditure on food actually is for people with lactose intolerance. No distinction was made between different levels of lactose intolerance. Köchling and Bischöff calculated additional monthly costs between 2 € and 20 € depending on the severity of lactose intolerance[11]. Limbacher *et al.* calculated additional monthly costs of 16 € and 14 € for a lactose-free diet for men and women[10], which corresponded to relative additional costs of 7·44 and 7·07 %, respectively. Eisold *et al.* determined additional costs of almost 11 € without differentiation between the sexes[13], which represented relative additional costs of 5·95 %. A comparison of the additional costs calculated in previous studies with those in this study (0·22–6·62 € per month) shows that the absolute values in this study are clearly lower. This finding was to be expected because the results of the optimisation model can be interpreted as a lower cost limit. The percentages of increases in the values in this study are only slightly lower (5·3 and 6·1 % for men and women in the 1g-lactose model, respectively). This finding is because the price level of the basic model was higher in previous studies compared to this study.

The comparable large differences of the absolute values of additional costs can be explained by the different methods and databases. The studies by Köchling and Bischoff, Limbacher *et al.* and Eisold *et al.* are based on food basket models in which conventional foods are replaced by dietetic foods. In these studies, as a first step, healthy food baskets are created according to the recommendations of nutrition societies (e.g. DGE) and are rated with prices. In a second step, some or all lactose-containing dairy products in the food baskets are replaced by lactose-free dairy product substitutes. Using this method, the food baskets are selected randomly and it is not clear if other healthy baskets with cheaper food combinations would be possible. The option of adjusting the food composition in principle (e.g. by reducing milk and dairy products) was not considered.

In the optimisation model used here, the most cost-effective healthy food baskets can be chosen for both the basic and lactose-reduced models. In contrast to the food basket models where only lactose-containing products are replaced by their lactose-free variants, it is possible to adapt the entire composition of the food basket when limiting the lactose contents. As shown in the results of this study, the optimisation model actually chose both methods (i.e. replacing lactose-containing products with their lactose-free variants and restructuring the whole food basket in a way that the proportion of dairy products slightly decreased whereas the proportion of other food groups slightly increased).

Another aspect that could explain why the absolute additional costs are higher in other studies compared to this study are the price data. Taking the milk price data as an example, while the prices of lactose-free milk are 56·9 % higher than those of normal milk in this study, they are 113·7 % higher in the study by Köchling and Bischoff. However, while the price data of previous studies were collected in only two or three grocery stores[10,11,13], the prices in this study were taken from a representative dataset for Germany that represented the purchases of 9429 adult households.

As the dataset on which this study is based dates from 2011, the question arises as to whether and to what extent the price premiums for lactose-free milk substitutes have changed since then. Information on current price premiums is provided by a 2019 study in which a store check was conducted in German supermarkets and discount stores[35]. The price premium of lactose-free milk was found to have changed slightly; that is, while it was 36 cents in the dataset of our study, it was 38 cents in the store check. Assuming a generally slightly decreasing price difference between lactose-free and lactose-containing milk and dairy products, it can be expected that lactose-free substitutes would be somewhat more represented in the modelled food baskets when using updated data and that the additional costs of the lactose-free food basket would decrease slightly.

Policy implications for social welfare legislation

The finding that a lactose-reduced diet causes additional costs is of particular interest in the context of social welfare payments. Social welfare recipients in Germany who suffer from lactose intolerance currently do not receive extra payments. The reason given by the German welfare legislation is that people with lactose intolerance can replace lactose-containing products with other foods rich in Ca, such as mineral water, cheese and some kinds of vegetables, and that this replacement is not linked with higher costs[14]. However, the central result of this study is that this substitution causes costs that are even higher than replacing lactose-containing products with lactose-free substitutes for which it is known that they are more expensive.

Overall, the models meeting different levels of lactose restrictions cause additional costs compared to the basic model (range, 0·2–6·1 %). It must be emphasised that these

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additional costs reflect the lowest possible values because of the formulation of the objective function of the linear optimisation model focussed on cost minimisation. Against this background and considering that the amount of social assistance reflecting the subsistence level is calculated on the basis of a normal diet including lactose-containing milk and dairy products, it can be concluded that recipients of social assistance suffering from lactose intolerance should receive additional benefits if the subsistence level is to be covered.

Limitation

The linear programming model used in this study aimed to identify precisely defined food quantities to compose the most cost-effective food basket considering the various restrictions. A widely known criticism for using this method in human nutrition is that precise food quantities may not be consumed under real-life situations. An example of this was semi-hard cheese with a quantity of 0·4 g/d (see Table 7). However, considering that the identified food baskets with their specified quantities are those that reflect the lowest possible additional costs of lactose-reduced diets, it can be assumed that all other baskets with quantities that are consumable under real-life situations would be more expensive. Therefore, it can be assumed that the central result of this study, that is, a lactose-reduced diet is more expensive than a lactose-containing diet, would remain unaffected if consumable food quantities were considered. To identify the actual costs, purchasable packaging sizes could additionally be considered in the model. This could be a subject for future research.

In this study, representative purchasing data were used to ensure that the food quantities of the optimised food baskets are consumable. As some of the purchased foods are discarded, the question arises as to what extent the data appropriately reflect consumable quantities. In general, food waste can be categorised as avoidable or unavoidable. Unavoidable food waste was considered in our study because the nutrient database (BLS) contains information on nutrients with and without inedible kitchen waste (e.g. peeled or unpeeled potatoes) and the respective form was linked to our purchasing data. In contrast, avoidable food waste could not be considered because there is insufficient information on this area from German food waste studies.

The use of enzyme preparations was not considered in the cost calculations because reducing lactose-containing foods is the main therapeutic intervention for people with lactose intolerance[36]. However, taking lactase-containing enzyme supplements can help in some situations to better manage lactose intolerance and improve quality of life[36].

For the present study, a comprehensive dataset that contains information on consumed quantities, prices and nutrients of foods and distinguishes between lactose-containing and lactose-free products was necessary. A dataset that met these requirements and was available to us was from 2011. For the actuality of the prices used to calculate the additional costs, it is particularly relevant to what extent the price premium for lactose-free substitute products has changed. A store check from 2019 showed that the price premium has slightly decreased in recent years (see the 'Additional cost of a lactose-reduced diet' section), which may result in lactose-free substitutes being slightly more represented in the modelled food baskets. With regard to the consumption restrictions, it can be assumed that these were defined broadly enough (10th–95th percentiles) so that they still reflect consumable quantities (see the subsections of 'Description of the linear programming model').

Conclusion

One of the main results of this study is that a wholesome lactose-reduced diet is more expensive than a wholesome lactose-containing diet. In addition, the most cost-effective form when switching from a normal diet to a lactose-reduced diet, while simultaneously meeting nutrient requirements, is to substitute regular milk by its lactose-free variant. These results have important implications for social benefit rates in the field of nutrition, which are meant to cover the absolute minimum required to survive (subsistence level). When people suffer from a serious form of lactose intolerance they have higher food costs. Avoiding lactose-containing milk and dairy products and switching to other foods rich in Ca, as often suggested, are even more expensive than switching to lactose-free dairy product substitutes.

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Supplementary material

For supplementary material accompanying this paper visit https://doi.org/10.1017/S1368980021002779

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