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Nutritional issues and dietary levers during gradual meat reduction – a sequential diet optimization study to achieve progressively healthier diets

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Short title: Nutrient challenges when reducing meat consumption

List of abbreviations

AA, Amino Acids

ANSES, French Agency for Food, Environmental and Occupational Health & Safety

DD, Diet Departure

EAR, Estimated Average Requirement

HDP, Healthy Dietary Pattern

Abstract

Background & Aims: Reducing meat consumption is a current trend and a strong prospect for the future in Western countries, but its dietary modalities and nutrient challenges remain poorly documented. Using diet optimization under a broad set of constraints, we tried to identify a sequential meat reduction transition and analyze its nutrient issues and dietary levers.

Methods: Based on the consumption of French adults (INCA3, $n=1\ 125$, 18-64 years old), we modeled a transition towards a nutritionally adequate healthy dietary pattern under the constraint of a gradual reduction in meat consumption in successive 10% steps. Using a multi-criteria optimization procedure, the diet modeled at each meat reduction step was to be healthier but close to the previous diet.

Results: The most significant changes occurred early in the modeled transition process, with drastic reductions in processed and red meats in favor of poultry, which rapidly became the predominant meat before gradually decreasing from 50% to 100% meat reduction. At the same time, whole grain products, fruits and vegetables consumption increased rapidly to reach a plateau from 50% meat reduction onwards. Some nutrients were limiting, in particular bioavailable iron and zinc, and vitamin A, but sufficient intakes were achieved by restructuring diets based on food groups other than meat. Other nutrients mainly supplied by meat such as vitamin B6 and B12, protein and indispensable amino acids, were never limiting.

Conclusion: Healthy and nutritionally adequate food patterns can be identified throughout a transition to complete meat reduction. After a 50% reduction in meat consumption, poultry is almost the only meat remaining and its further reduction makes the diet only marginally healthier.

Keywords: diet optimization; healthy dietary patterns; gradual meat reduction; nutrient adequacy; dietary habits

Introduction

Plant-based diets have consistently been associated with long-term health, *i.e.*, a lower risk of chronic diseases (1–4). Several variants of these healthy and sustainable diets have been identified using different approaches such as the Mediterranean diet (5), the "new Nordic diet" (6) and the EAT-Lancet diet (4), which mainly involve a high consumption of plant-based products and a moderate to no consumption of meat. These diets generally contain less saturated fatty acids (SFA) and sodium, and are more nutritionally adequate than current Western diets for a number of nutrients such as fiber and folate (7–9). For many other nutrients, achieving adequate nutrient intakes may become more challenging as the proportion of animal products diminishes (10–12). In Western countries, a reduction of meat consumption is a current trend in some subgroups of the population (13) and a strong prospect for the years to come (14). This trend can be explained by concerns regarding human health, animal welfare and the environment, amongst others (15–19). Meat, and especially processed meat, contributes to intakes of SFA and sodium (20,21), and its reduction could help to reduce excessive intakes of these nutrients (22). However, meatless diets raise some specific nutrient issues. Meat and especially offal are important sources of protein and indispensable amino acids (AA) (23) and supply essential minerals and vitamins such as iron, zinc, selenium and vitamins A, B6 and B12, for which some insufficient intake and/or deficiency has been documented in adults (24–27). The bioavailability of some of these nutrients is generally lower under plant-based diets than animal-based diets (28); *e.g.* in individuals with adequate iron status, heme iron in meat is much more bioavailable than non-heme iron in plant-based products (29,30). Meeting nutritional reference values with a diet containing less meat may thus be challenging regarding a number of these nutrients (31,32). Based on the current trend to reduce meat consumption and the paucity of data in the literature to rigorously evaluate the dietary characteristics of low-meat or meat-free diets that would render them nutritionally adequate, data are required to understand which changes in the diet, as close as possible to dietary habits, should be made when decreasing meat consumption to maintain or improve diet quality (33–37). Our objective was therefore to design diets involving a gradual reduction in meat in order to identify the

most salient nutrient issues and possible efficient dietary levers, *i.e.* the food groups for which changes in consumption would supply these limiting nutrients while also aligning with improvement in the dietary pattern.

Methods

Input data

We used food consumption data on males ($n=564$, 18-64 years old) and pre-menopausal females ($n=561$, 18-54 years old), not identified as under-reporters, in the French INCA3 national study conducted in 2014-2015 (Supplemental Figure 1). The survey design and methods have been described in full elsewhere (38,39). The socio-demographic characteristics and lifestyles of the study population are presented in Supplemental Table 1. Briefly, food and beverage intakes were assessed using three unannounced non-consecutive 24h-dietary recalls collected by trained interviewers assisted by dietary software. Portion sizes were estimated using validated photographs (38). Nutrient intake was calculated using the 2016 nutritional composition database from the French *Centre d'Information sur la Qualité des Aliments* (CIQUAL) (40). Food items ($n=1\,533$) were categorized into 45 food groups (31) (Supplemental Table 2). Food group consumptions were calculated at the population level for males and females separately. For each sex, the nutrient content of each food group (41 nutrients) was calculated, as the mean nutrient content of food items constituting the food group weighted by their respective contributions to the food group consumption in the considered sex (32). In order to check that adequate intakes of indispensable AA were maintained in the modeled diets, we used a database on the AA composition of foods, collecting published French analyses and international databases and thus extending our previous database (41) (Supplemental Method 1).

Multi-criteria diet optimization

To address the issue of diet optimization, where the decision variables were the daily intakes of 45 food groups, we used multi-criteria optimization to identify an optimized diet with a maximal health

profile and minimal deviation from the current diet, under the constraint of covering sex-specific nutrient references, using the OPTMODEL procedure under SAS software (SAS Institute®, Inc., Cary, NC, USA, version 9.4). The *HDP (Healthy Dietary Pattern)* criterion sets dietary objectives based on epidemiological studies that have evaluated associations between food group consumption and chronic disease risk (32,42) as used to prepare French dietary guidelines (43). It consisted in reducing the consumption of red meat (including beef and veal, pork and other meats, and offal), processed meat and soft drinks while increasing the consumption of vegetables, fruits and whole grain products. The *HDP* criterion was expressed and maximized as follows:

$$\text{Max } HDP = \sum_{i=1}^3 \left[\frac{\text{Opt}(i)}{\text{P95}(i)} \right] - \sum_{j=1}^3 \left[\frac{\text{Opt}(j)}{\text{Max}(j)} \right]$$

where *i* denotes the food groups to be increased (vegetables, fruits, and whole grain products), *j* denotes the food groups to be decreased (red meat, processed meat and soft drinks), *Opt*(*i*) and *Opt*(*j*) are the optimized intakes of food groups *i* and *j*, respectively (in g/d), *P95*(*i*) is the current 95th percentile intake of food group *i* (in g/d), and *Max*(*j*) is the upper limit of intake for food group *j* (in g/d). The upper limit of intakes for red meat, processed meat and soft drinks were 71, 25, and 263 g/d, respectively, as defined by the French Agency for Food, Environmental, and Occupational Health Safety (ANSES) (43).

The *DD (Diet Departure)* criterion is used to minimize deviation from the observed diet in order to account for dietary inertia (44). The *DD* criterion was expressed and minimized as follows:

$$\text{Min } DD = \sum_{k=1}^n \left[\frac{\text{Obs}(k) - \text{Opt}(k)}{\text{SD}(k)} \right]^2$$

where *k* is the number of food groups, *Obs*(*k*) and *Opt*(*k*) are the observed and optimized consumptions of food group *k* (in g/d), respectively, standardized by dividing by *SD*(*k*), the current standard deviation of the consumption of food group *k*.

As some food groups were considered to be more easily substitutable, they were grouped together in the same food group *k* in *DD* so that the substitutions within the following groups would not weight

DD: fruits (fresh/dried/processed), breads (refined/whole grain), other starch-based products (refined/whole grain), vegetable fats (low/high in α -linolenic acid), meat (poultry/red meat, excluding offal), soft drinks (drinks with added sugars/fruit juices), fish (fatty/lean), fresh dairy products (natural/sweetened), and soups/bouillons.

The optimization procedure consisted in maximizing *HDP* while minimizing *DD* without specific weighting (1:1), as previously performed by us (32) and before that by the ANSES (31,43). With this scalarization method (weighted sum method with equal weights for *HDP* and *DD*), the identified solution corresponded to the best compromise between a healthier diet and a diet as close as possible to the current one, by considering these two objectives as being of equal importance (45).

Nutritional and acceptability constraints

To ensure the nutritional adequacy of the modeled diets, we used a set of nutritional constraints related to 35 nutrients, presented in **Table 1** and in Supplemental Table 3. These sex-dependent constraints were based on the ANSES 2016 reference values (26). We also constrained total energy intake within $\pm 5\%$ of the estimated mean energy intake of the French INCA2 national study conducted in 2006-2007 (2600 kcal for males and 2100 kcal for females) (46). One exception was vitamin D, for which we did not set any lower constraint because the reference value is known to be far too high to permit a solution from diet optimization (31,32).

For iron and zinc, reference values were based on bioavailable iron and zinc calculated from dietary intakes using equations to predict their absorption, as detailed in a previous work by our group (32). Regarding the nutrient constraints for bioavailable iron and zinc, we used threshold values lower than current reference values, corresponding to a deficiency prevalence of 5% in each sex (Table 1 and Supplemental Table 3), because such flexibility would enable the identification of diets being apparently healthier overall, with a better balance in terms of Disability Adjusted Life Years (DALYs) averted due to less cardiometabolic disease despite a higher prevalence of iron-deficiency anemia (32). As previously performed again (32), flexibility for bioavailable iron and zinc was introduced by adding

in the objective function, in addition to its *HDP* and *DD* terms, two goal variables that would minimize any violation of these relaxed nutrient constraints. The reference values used as goals were set for bioavailable iron at 1.72 mg/d for both sexes and for bioavailable zinc at 3.63 mg/d for males and 3.23 mg/d for females (26,31). An alternative scenario without flexibility on bioavailable iron and zinc (*i.e.*, with bounds set at current references values, and without goal variables) was also tested. In addition, to take account of the poorer digestibility of plant proteins, a 5% penalty was applied to protein intake from plant protein food items, as previously described (47). Dietary constraints were also applied to the food groups included in the *HDP* criterion where consumption was to be reduced: red meat (beef and veal/pork and other meats/offal), processed meat and soft drinks (soft drinks/fruit juice) were limited to the max values used in the *HDP* criterion of 71 g/d, 25 g/d, and 263 mg/d, respectively (43). Finally, in order to take account of French dietary guidelines on fish consumption (48), we added two additional constraints to limit total fish consumption to 39 g/d and oily fish consumption to 26 g/d. Furthermore, acceptability constraints were used to keep the modeled intakes by food group within the range observed for each sex (Supplemental Table 4). The acceptability constraints included lower and upper values that corresponded to the 5th or 95th percentiles of consumption for all food groups except those with an upper limit set as a dietary constraint (red meat, processed meat and soft drinks). In the same way as for the *DD* criterion, the most substitutable food groups in the acceptability constraints (see above) were grouped together to define their lower and upper bounds as the 5th or 95th percentiles of their total consumption. As some values were sex-dependent in both the nutritional and acceptability constraints and also in the *HDP* and *DD* criteria, optimization was performed at the population level for males and females separately.

Gradual meat reduction constraint

Total meat consumption (poultry, red meat and processed meat) was constrained to be diminished by at least x% of its observed value in a stepwise manner, with x taking successive values of 10%, 20%, 30%, etc. to reach meat-free diets (x=100%). In addition, we forced a non-degradation constraint of

the *HDP* criterion, so that it could only increase or remain the same from one step to another along the transition. Adding this constraint made it possible to estimate what additional *HDP* gain could be achieved in the final steps of meat reduction until its elimination, where high *DD* costs were required for small *HDP* gains. It was also needed to make sure that the diets were progressively healthier. At each step, *DD* was calculated with reference to consumption at the previous step.

Standardization of constraints to compare their relative influences

We estimated the dual values associated with each constraint, *i.e.*, the potential gain in the objective function that would result from relaxing the limiting bound of the considered constraint by one unit. All constraints were standardized on the value of their limiting bounds (49), so that the standardized dual values (representing the effect of a 100% relaxation of the limiting bound) could be compared numerically with each other, and the limiting constraints for nutrient and food group intakes could be classified from the most to the least limiting, as previously explained (32).

Results

Changes to dietary patterns and objective values during the transition towards less meat

Modeled diets could be identified (*i.e.* solutions could be found) at each step of the meat reduction transition in both sexes (**Figure 1**). Compared to the observed diet, the modeled diets were increasingly healthier along the transition (*i.e.*, increasing *HDP*), with more fruits and vegetables alongside a considerable substitution of refined grain products with whole grain products and a reduction in red meat, processed meat and soft drinks (Figure 1 and Supplemental Table 5). These dietary changes occurred very early and gradually during the first half of the transition before slowing down, with dietary patterns remaining generally much more stable from 50% to 100% of meat reduction (Figure 1).

At the first step, total meat consumption decreased more than the imposed constraint: reductions of 20% in females and more than 30% in males were thus obtained when a reduction of at least 10% was

required at that point. The meat reduction constraint was not active and had no influence on the modeled diets (*i.e.*, the modeled diets were the same whether this constraint was considered or not). The meat reduction constraint only became active (*i.e.*, limiting) at the 20% step in females and 40% step in males, where the effective reductions in total meat consumption were then equal to their prescribed values (Supplemental Table 6). When optimizing according to the *DD* criterion only (no optimization on the *HDP* criterion), and in order to determine the optimized diet closest to the observed diet ensuring nutrient adequacy, meat was similarly reduced by 20% in females and 30% in males (results not shown). Furthermore, from the first step of the meat reduction transition, there was a redistribution within meats that involved the drastic reduction or elimination of red and processed meats that was offset by a significant increase in poultry consumption (considered substitutable for red meat without impacting *DD*), which became the predominant meat consumed from the 10% step and subsequently (**Figure 2**). Regardless of sex, the 50% meat reduction step still retained a relatively high level of poultry (48 to 78 g/d, *i.e.* ~ 3 to 4 servings of 120 g per week) (Supplemental Table 5), but poultry was then gradually and linearly reduced during the second half of the transition (Figure 2). The most notable improvements in the *HDP* criterion were achieved early in the transition, with large *HDP* gains associated with small *DD* costs during the first steps of meat reduction (**Figure 3**). From the point where the *HDP/DD* yield was falling sharply, little additional *HDP* gain was achieved by subsequent dietary changes that mainly consisted in a gradual reduction of poultry consumption (whereas the overall dietary pattern remained globally stable through to the end). As from a 50% meat reduction, the *HDP* criterion reached 85-90% (depending on sex) of its maximal value finally achieved with meat-free diets. At that point, fruit and vegetable consumptions (among the groups to be promoted under *HDP*) reached their 95th percentiles of consumption (*i.e.*, the upper bounds of the acceptability constraints) and the food groups to be reduced were nearly removed (Supplemental Tables 4 and 5). Late transition changes involved food groups with smaller inter-individual variations in the observed diet (*i.e.*, with lower SD present in the denominator of the *DD* criterion), corresponding

to *DD* increases that were not always apparent in our diet representations by food family grouping (Figures 1 and 3 and Supplemental Table 7).

Changes to nutrient intakes and nutritional adequacy

By construction, the intakes of sodium, SFA, and sugars (excluding lactose) which were excessive with the observed diets (the latter in males only), were reduced under all modeled diets, while remaining stable at or near their upper allowed reference values (Table 1). Reciprocally, the intakes of vitamin C, linoleic acid, α -linolenic acid, EPA, DHA, fiber, vitamin A, iodine and potassium, which were insufficient in the observed diets (the latter three in females only), were increased above their reference values (Table 1).

Bioavailable iron and zinc were below their current reference values at all steps in meat reduction (with variations ranging from -33 to -24% for bioavailable iron and -25 to -11% for bioavailable zinc over the transition and in both sexes), but by construction they were above their safety thresholds, thus ensuring a prevalence of deficiency <5% (Table 1).

In models without flexibility on bioavailable iron and zinc that were set at their current nutritional references, these two nutrients were the most limiting from the start of the transition and even blocking at the end, since we were able to identify diets reaching 70% meat reduction (but no higher) in both sexes (Supplemental Figure 2). By contrast, in our main analysis with flexibility on bioavailable iron and zinc, the model converged up to full meat removal, and these two nutrients were no longer the most limiting.

Sodium, linoleic acid, α -linolenic acid, EPA, DHA, and sugars (excluding lactose) were limiting nutrients in both sexes and at all steps of meat reduction (except EPA and DHA that were not limiting at some steps in males) (Table 1). Vitamin C, vitamin A, iodine, SFA, and fiber were also limiting in both sexes, but only at some early meat reduction steps, except for vitamin A that became limiting again during the final steps in males (Table 1). Bioavailable iron and potassium were limiting at some early steps in females only (Table 1). In terms of relative importance, sodium was always the most limiting nutrient

whatever the sex and transition step (except in the 40%, 50%, and 100% meat reduction steps in males), often followed (and sometimes surpassed in males) by sugars excluding lactose (Supplemental Table 8). Vitamin A was limiting less frequently, except in the final transition steps in males (from the 70% step onwards) where it was the second most limiting nutrient after sodium.

Group B vitamins (and particularly vitamins B6 and B12), protein and selenium were never limiting (Supplemental Table 3), and their intakes were maintained above reference values throughout the transition to meat-free diets (Supplemental Table 3). Intakes of protein and indispensable AA were much higher than their current reference values, including with the meat-free diets (Supplemental Table 9).

Changes affecting food group contributions to nutrient intakes

We examined the contributions of each food group to nutrient intake for nutrients that were limiting, or where meat was a significant source in the observed diets (contributing to >10% of nutrient intake). In the observed diet, meat contributed notably to the intakes of bioavailable iron (38-47%, depending on sex), bioavailable zinc (36-43%), vitamin A (16-28%), vitamin B12 (34-43%), vitamin B6 (26-29%), protein (33-37%) and selenium (10-12%), but very little to iodine intake (4-6%).

In the modeled diets, as the animal food groups other than meat (seafood, dairy products and eggs) were maintained or increased while meat was reduced (Figure 1), they played an increasing role in the intake of some nutrients such as bioavailable iron and zinc, vitamins A and B12, and iodine as the transition progressed (**Figure 4** and Supplemental Figure 3). Concerning bioavailable iron and zinc, the contribution of seafood thus increased during the second half of the transition. Nevertheless, during the late transition steps of high meat reduction, the sum of animal food groups only achieved modest contributions to bioavailable iron (23-24%) and bioavailable zinc (38-43%), and more than half of the bioavailable iron and zinc were supplied by plant-based food groups, although the absorption of non-heme iron and zinc was impaired by the increase in phytate which mainly came from whole grain products. Therefore, comparing the observed and meat-free diets, iron and zinc intakes were globally

maintained (at around 12-13 mg/d and 9-10 mg/d, respectively) but their absorption rates decreased (from 13% to 9% and from 34% to 28%, respectively) (Supplemental Table 10).

The vitamin A intake was equal to or slightly higher than its reference value, as a function of meat reduction step (Table 1 and Figure 4). With meatless diets, vitamin A was mainly supplied by fruit and vegetables which contributed to ~54% of its intake in meat-free diets (vs. ~23% in observed diets).

Intakes of vitamin B12, protein, vitamin B6, and selenium were well above their reference values (Supplemental Table 3). For vitamin B12, the contribution of seafood increased during the first half of the transition, effectively taking over from meat to ensure an adequate intake (Figure 4). For protein, vitamin B6 and selenium, plant-based food groups were good dietary levers whose gradual increases contributed to maintaining adequate intakes until meat-free diets were reached (Figure 4 and Supplemental Figure 3).

Discussion

In this work we identified a dietary transition of meat reduction that consisted in a series of modeled diets which were nutritionally adequate and consistent with healthier dietary patterns. Beyond a 50% meat reduction, subsequent reductions were much less effective in improving the healthiness of the dietary profile, but a healthy meat-free diet could be identified in both sexes. Except for vitamin D and bioavailable iron and zinc, all nutrients with insufficient intakes under the observed diet (vitamin C, linoleic acid, α -linolenic acid, EPA, DHA, and fiber, as well as vitamins A and B6, folate, calcium, iodine, and potassium in females) reached reference values under the modeled diets. One important finding is our identification of limiting nutrients which may constitute nutritional issues during gradual meat reduction, and the dietary levers identified as food groups in which changes would supply these limiting nutrients while also improving the dietary profile. In our study, limiting the sodium intake to its upper limit appeared to strongly determine dietary solutions at each step, as is often the case in diet optimization, but reducing meat consumption contributed to these solutions (50). Likewise, reducing red and processed meats in favor of poultry ensured lower and more appropriate levels of

SFA, as soon as the first step of meat reduction. Before 20% meat reduction in females and 40% in males, the reduction of meat in the modeled diets was stronger than that required, which means that reducing meat was not limiting at those steps of the transition and was indeed useful for modeling healthy and nutritionally adequate diets. Throughout the transition, nutritional constraints limited the identification of diets that could be more consistent with the optimization objectives (*i.e.*, diets that could be both healthier and remain close to observed diets), but many of the limiting nutrients were not supplied by meat, such as iodine or fiber which were limiting as soon as during the first steps of the transition. The dietary solutions we identified involved increasing food groups that are sources of these nutrients. By contrast, some nutrients largely contributed by meat proved to be an issue: bioavailable iron and zinc and vitamin A. It was possible to reach sufficient intakes of these nutrients during the transition by reorganizing the diets using food groups other than meat (fruits and vegetables, whole grain products and seafood). Other nutrients to which meat was initially a major contributor, such as vitamins B6 and B12, protein and indispensable AA, were supplied in ample amounts in all the modeled diets.

Another important finding was that an improvement in alignment with a healthy dietary pattern (*HDP* criterion) was very effective during the first steps of the transition, with virtually full alignment at the 50% meat reduction step (where fruits and vegetables had already reached their maximal allowed values set at the 95th percentile of their current observed consumptions). At this step, meat intake consisted almost exclusively of poultry, in much larger quantities than in the observed diets. Given that red meat and processed meat tend to be reduced in order to comply with the objective set in the *HDP* criterion, it was expected that scenarios of reducing meat intake would favor poultry. Indeed, in the literature, poultry has been shown to be a healthier alternative to red and processed meats when considering the risk of chronic diseases (51,52). A further reduction in meat intake, once mostly replaced by poultry (*i.e.*, from 50% of meat reduction), proved to be limiting in the identification of better diets, which means that poultry is useful to optimize diets, and particularly as a source of bioavailable iron and zinc during the first half of the transition only. Of note, the fact that red meat

was substituted by poultry rather than by plant foods that may be effective dietary levers, such as legumes, could be ascribed in part to the weight we gave to dietary inertia, favoring internal substitutions between meats. We considered that, when decreasing total meat, it was more acceptable/feasible than increasing very different food groups which are little consumed presently. Therefore, our results do not mean that legumes and other plant protein sources that are nutrient-dense could not be important for reducing meat if more disruptive dietary shifts are considered.

The few studies which aimed to prospectively identify modeled diets with both health-promoting dietary patterns and relatively low meat consumption used methods other than optimization, such as modeling the substitution of meat with alternatives (53,54). Overall, our results were consistent with a previous observational study conducted on the same population which simulated partial or total meat replacement with plant-based substitutes, inasmuch as it was found that substitutions also led to diets that were more adequate for fiber, linoleic acid, α -linolenic acid, folate, and SFA, but with lower levels of bioavailable iron and zinc (53). That study also reported a reduction in the adequacy of vitamin B12 and riboflavin intakes, whereas in the present study they were maintained above their reference values in all modeled diets (+20% minimum throughout the transition in both sexes). This difference was due to the fact that in the previous and specific substitution modeling study, the meat substitutes were low in vitamin B12 and riboflavin whereas the present study showed that remodeling of the diet during the sequential optimization process toward a healthier dietary pattern supplied those vitamins in quantities similar to or even higher than those resulting from the reduction in meat consumption. Restructuring the entire diet was thus clearly more efficient than using simple selective substitutes for meat.

Uncertainties remain regarding the estimated physiological reference values for iron and zinc and the resulting reference values (32,55). In a previous work, we had shown that the current high reference values for bioavailable iron and zinc tend to limit the overall health benefits of a healthier dietary pattern (32). Accordingly, in order not to over-determine the model in the present work, we did not impose the current reference values for bioavailable iron and zinc but lower minimum threshold values

that would secure an acceptable level of these nutrients in the population (with an overt deficiency prevalence <5%) and add a goal in the objective to favor values above this lower threshold and as close as possible to the reference values. With this flexibility, the amounts of bioavailable iron and zinc remained relatively high, except in females where bioavailable iron levels in the modeled diets were close to the lower threshold, which would correspond to a prevalence of iron-deficiency anemia similar to that currently observed (4.1%) (56).

Our study has revealed the existence of dietary levers for low-meat or meat-free diets that do not jeopardize nutrient adequacy. We found alternate contributors for vitamin A, mostly fruits and vegetables. Less expected was the finding regarding levers for bioavailable iron and zinc during the transition since meat, and especially red meat, is rich in heme iron which is 2 to 3 times more bioavailable than the non-heme iron found in plant-based foods (29,57). Solutions consisted in increasing intakes of plant-based foods (fruits, vegetables, whole grain products and legumes) and seafood, although plant foods also increased the intake of phytate, a potent inhibitor of non-heme iron and zinc absorption (28,58). Indeed, the fractional absorption rates for iron and zinc were lowered in the model compared to the initial observed diets, but their intakes were maintained or increased during the transition, despite early and drastic reductions due to red and processed meats. These results are consistent with other published studies which reported that although vegetarians have lower iron stores, any adverse health effects of lower iron and zinc absorptions have not been demonstrated with the varied, plant-based diets consumed in high-income countries (59–61).

On the other hand, our study also revealed nutrients largely contributed by meat in the observed diets that were not at issue during the modeled transition. In particular, we have shown that a combination of protein sources other than meat could achieve high levels of protein and indispensable AA, including lysine and methionine. This was in line with other studies which concluded that even when eating a diet of limited variety, significant amounts of total protein could be obtained from a high intake of plant foods that are low in protein, including fruits and vegetables (62), and that total protein and

indispensable AA intakes from low-meat diets are apparently sufficient for adults in Western countries (63,64).

During the second part of the transition, when poultry intake was reduced, animal food groups (seafood, dairy products and eggs) were maintained or increased but the quantities never reached their maximal allowed values, except for the "Mollusks and crustaceans" food group where quantities reached their 95th percentile of consumption in both sexes. At the 100% meat reduction step, the modeled diets corresponded to pesco-lacto-ovo-vegetarian diets. With the exception of meat, we imposed staying within the observed sex-specific ranges of consumption, but it is possible and perhaps necessary to explore other potential diets that might depart further from these ranges (*i.e.* exceeding the 95th percentiles of consumption for some food groups) in order to describe other low-meat or semi-vegetarian diets, as has been done during previous studies (50,65).

Strengths and limitations

Our multi-criteria approach to diet optimization considered a wide range of nutrients, including bioavailable iron and zinc, and the relative digestibility of protein. Our study was based on observed diets in French adults with similar background intakes – although somewhat higher in meat – and similar reference values when compared to other Western countries (26). One limitation is that we only studied one transition for each sex and in a wide age range (18-54 years old for females, and 18-64 years old for males), and this population-level optimization does not account for variations in the observed starting diets that might, for example, originate from the socioeconomic characteristics of the population, which may warrant further detailed studies.

Conclusion

We have identified a possible dietary transition from current relatively meat-rich Western diets to nutritionally adequate and healthier diets involving a gradual reduction in meat consumption. Healthy dietary patterns, which include only poultry as meat, were identified from a 50% meat reduction and

onwards. This study demonstrates that it is possible to reduce the share of meat in the diet, and even remove it totally, without jeopardizing nutrient security (provided that the diets are properly structured). It thus offers nutritional and dietary lessons on transitions toward healthy diets that are low in meat. Nutrients whose intake was largely contributed by meat in the observed diets, such as total protein, indispensable AA and vitamin B12, were not a limiting factor for the reduction in meat consumption, but when remodeling diets, it was necessary to find adequate sources of bioavailable iron and zinc and vitamin A.

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AD, HF, EK-G, and FM: designed the research; AD, HF: conducted the research; AD, HF, EK-G, and FM analyzed the data; MS, EP, and J-FH provided methodological support; AD drafted the first version of the manuscript, AD, FM and HF wrote the manuscript and all authors provided critical comments on the manuscript. AD and HF had primary responsibility for the final content, and all authors read and approved the final manuscript.

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TABLE 1. Daily intakes of limiting nutrients in observed and modeled diets as optimized to be healthier while taking account of dietary inertia ¹ during a sequential transition towards diets containing less meat, according to gradual constraints for meat reduction (from at least 10% to 100%) in males and females (INCA3 survey, $n=564$ males and $n=561$ females)

Legends for Figures

FIGURE 1. Average daily consumption of food groups in observed (Obs) and modeled diets as optimized to be healthier while taking account of dietary inertia during a sequential transition towards diets containing less meat, according to gradual constraints for meat reduction (from at least 10% to 100%) in males (panel A) and females (panel B) (INCA3 survey, $n=564$ males and $n=561$ females)

In each $x\%$ modeled scenario, total meat consumption was diminished by at least $x\%$ of its observed value. For clarity, the 45 modeled food groups are not shown here but were grouped into broader categories that were included in the *Healthy Dietary Pattern* criterion (such as red meat, processed meat, soft drinks, grain products, fruits and vegetables) or represented other protein sources (such as poultry, seafood, dairy products, eggs, legumes and nuts). The remaining food groups were grouped as "others" (8 groups) and "other drinks" (3 groups) and are not presented in Figure 1. Detailed food categories are presented in Supplemental Table 2.

FIGURE 2. Daily consumption of meat by type (processed meat, pork and other meats, offal, beef and veal, poultry) in observed (Obs) and modeled diets as optimized to be healthier while taking account of dietary inertia during a sequential transition towards diets containing less meat, according to gradual constraints for meat reduction (from at least 10% to 100%) in males (panel A) and females (panel B) (INCA3 survey, $n=564$ males and $n=561$ females)

In each $x\%$ modeled scenario, total meat consumption was reduced by at least $x\%$ of its observed value. The black line shows the minimal reduction set at each step. "Other meats" includes lamb, game, rabbit, and horse meat.

FIGURE 3. Values of the *Healthy Dietary Pattern* (HDP) and *Diet Departure* (DD) criteria of the objective function throughout the optimization steps of the meat reduction transition from the initial observed diets in males and females

In each $x\%$ modeled scenario, total meat consumption was diminished by at least $x\%$ of its observed value.

a.u., arbitrary unit.

FIGURE 4. Contribution of food groups to bioavailable iron and zinc, vitamins A and B12 and protein in observed (Obs) and modeled diets as optimized to be healthier while taking account of dietary inertia during a sequential transition towards diets containing less meat, according to gradual constraints for meat reduction (from at least 10% to 100%) in males (panel A) and females (panel B) (INCA3 survey, $n=564$ males and $n=561$ females)

In each x% modeled scenario, total meat consumption was diminished by at least x% of its observed value. For clarity, the 45 modeled food groups are not shown here but were grouped into broader categories were included in the Healthy Dietary Pattern criterion (such as red meat, processed meat, soft drinks, grain products, fruits and vegetables) or represented other protein sources (such as poultry, seafood, dairy products, eggs, legumes and nuts), and the remaining food groups were grouped as "others" (8 groups) and "other drinks" (3 groups). Detailed food categories are presented in Supplemental Table 2. As iron and zinc intakes took into account their bioavailability, protein intake took into account the poorer digestibility of vegetable proteins (see Methods for detailed information). For each nutrient, current reference values and security thresholds (for bioavailable iron and zinc) are represented by solid and dashed lines, respectively (see Methods for detailed information on how flexibility was allowed on bioavailable iron and zinc using goal variables, and Table 1 and Supplemental Table 3 for detailed values on current references and security thresholds).

Figures show nutrients that are largely contributed by meat in the observed diets.

FIGURE 1.

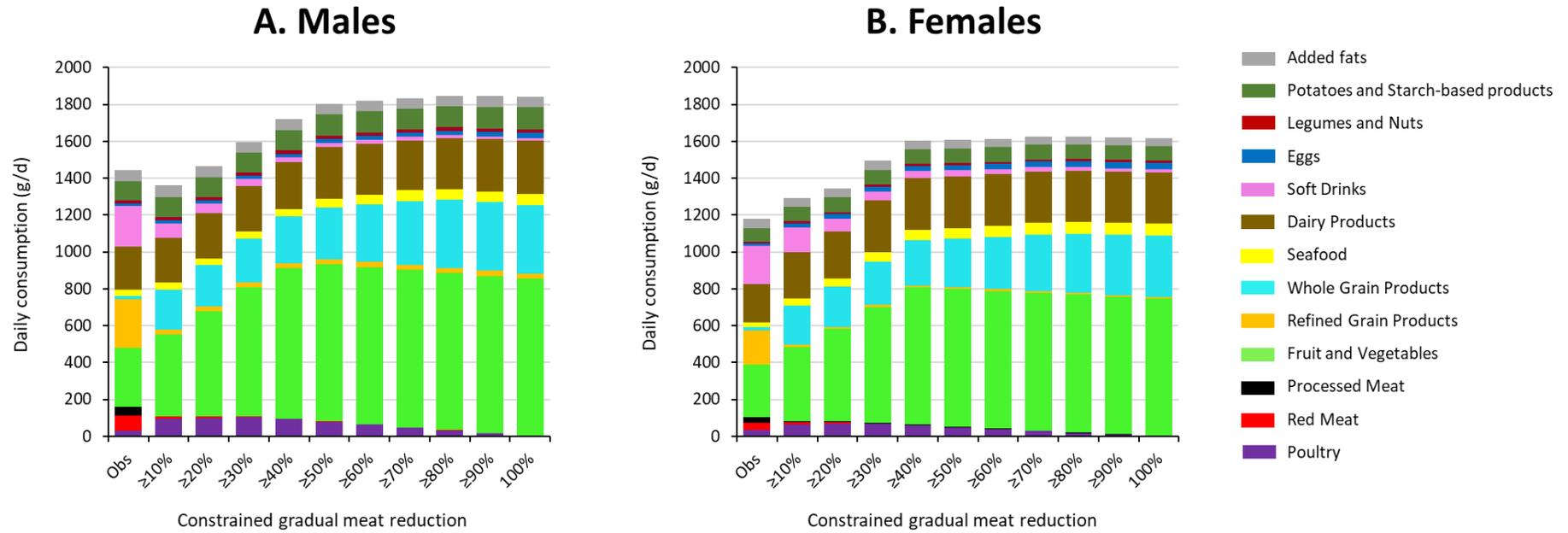


FIGURE 2.

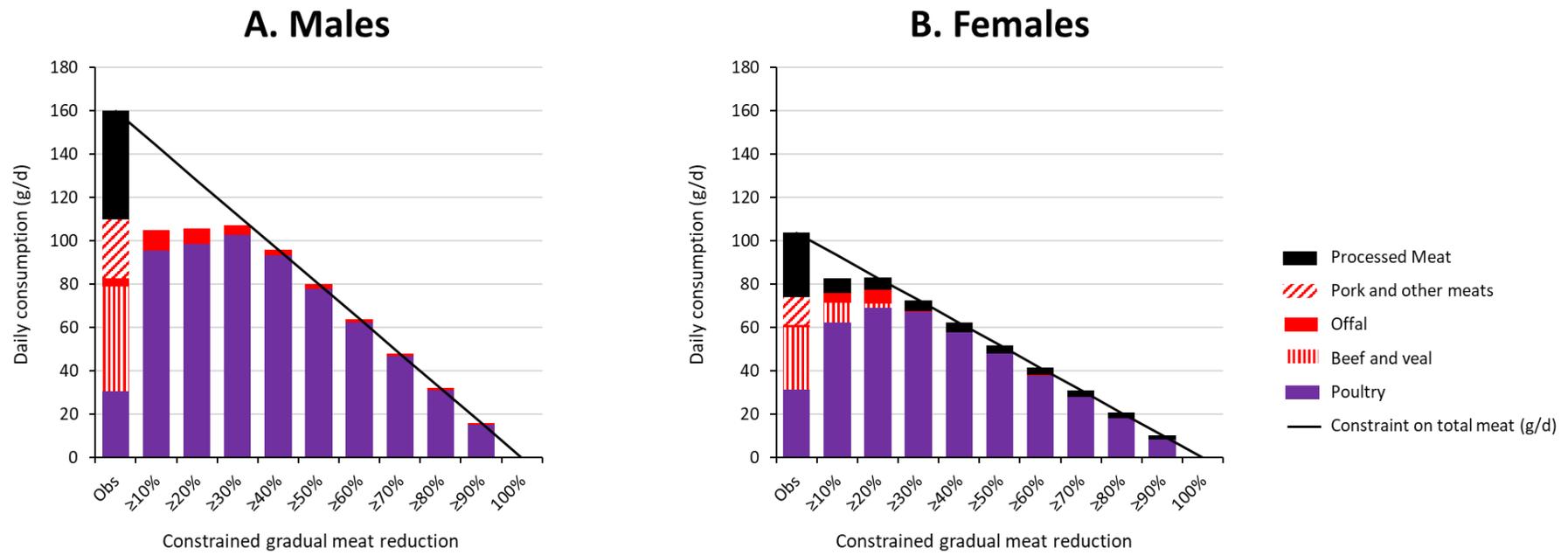


FIGURE 3.

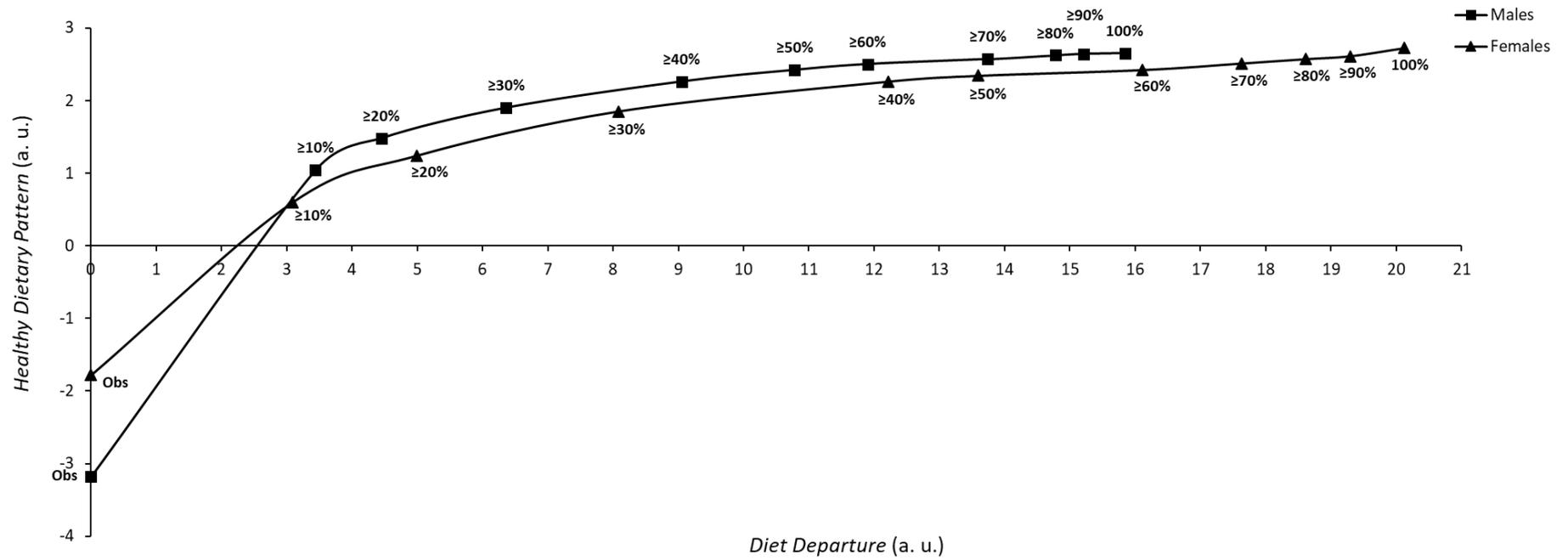
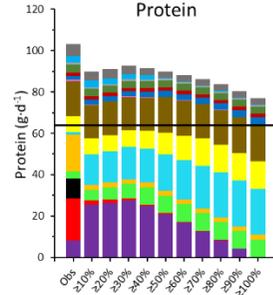
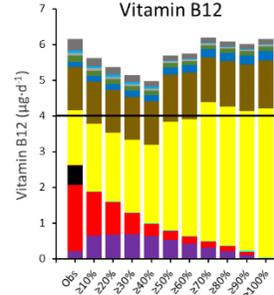
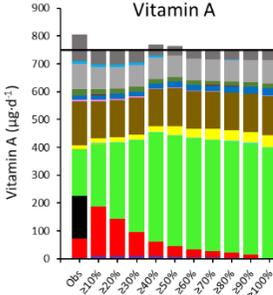
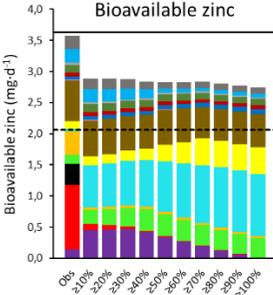
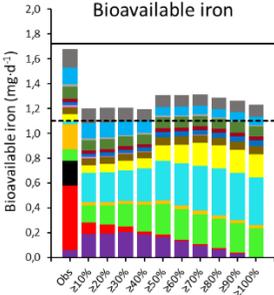


FIGURE 4.

A. Males



- Others
- Other drinks
- Added fats
- Potatoes and Starch-based products
- Legumes and Nuts
- Eggs
- Soft Drinks
- Dairy Products
- Seafood
- Whole Grain Products
- Refined Grain Products
- Fruit and Vegetables
- Processed Meat
- Red Meat
- Poultry
- Current reference value
- - - Security threshold

B. Females

