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Griffin, B. A., Mensink, R. P. and Lovegrove, J. A. ORCID: <https://orcid.org/0000-0001-7633-9455> (2021) Does variation in serum LDL-cholesterol response to dietary fatty acids help explain the controversy over fat quality and cardiovascular disease risk? *Atherosclerosis*, 328. pp. 108-113. ISSN 0021-9150 doi: 10.1016/j.atherosclerosis.2021.03.024 Available at <https://centaur.reading.ac.uk/99743/>

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To link to this article DOI: <http://dx.doi.org/10.1016/j.atherosclerosis.2021.03.024>

Publisher: Elsevier

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Does variation in serum LDL-cholesterol response to dietary fatty acids help explain the controversy over fat quality and cardiovascular disease risk?

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Declarations of interests.

JAL is Deputy Chair of the UK Government's Scientific Advisory Committee on Nutrition (SACN) and was a member of SACN's Working Group on 'Saturated Fats and Health'. JAL Chairs and RPM is Deputy Chair of the International Life Sciences Institute (ILSI) committee on 'Individual Saturated fatty acids and Cardiovascular Risk'.

1. Abstract

Background and Aims: Controversy over fat quality and cardiovascular disease risk stems from a series of meta-analyses of prospective cohort and randomised intervention trials, which found little evidence for a significant relationship between the intake of saturated fat and disease endpoints. Possible explanations for these null findings include difficulties inherent in estimating true food intake, the confounding effects of macronutrient replacement and food composition, and marked inter-individual variation in the response of serum LDL-cholesterol. The aim of this narrative review was to present evidence for the existence and origins of variation in serum LDL-cholesterol response to the replacement of dietary saturated fat, and its potential to explain the controversy over the latter. **Methods/Results:** The review provides evidence to suggest that variation in LDL-responsiveness may harbour significant potential to confound the relationship between saturated fat and atherosclerotic cardiovascular disease risk, thus undermining the effectiveness of the dietary guideline to replace saturated fat with unsaturated fat. **Conclusions:** the identification and application of a simple biomarker of this phenomenon, would make it possible to tailor dietary guidelines to LDL responsive individuals, who stand to gain a greater benefit to their cardiovascular health.

46

47 **2. Introduction**

48 **Serum low density lipoprotein, saturated fat; consensus amidst controversy**

49 Since the discovery of low-density lipoprotein (LDL) in 1955, knowledge of its now established
50 roles as a causal risk factor in the pathogenesis of atherosclerotic cardiovascular disease
51 (ASCVD) and target of cholesterol-lowering therapy, has made an incalculable contribution to
52 the reduction in morbidity and mortality from this disease worldwide. This remarkable
53 progress in medical science has occurred against a backdrop of controversy and scepticism
54 over the strength of evidence to support the link between raised LDL cholesterol and ASCVD
55 [1], and more recently, dietary recommendations to lower serum LDL by reducing intake of
56 saturated fatty acids (SFA) [2,3]. In 2017 and 2020 [4, 5], consensus panels for the European
57 Atherosclerosis Society (EAS) concluded that LDL is a causal risk factor for the development of
58 ASCVD. Simultaneously, independent expert scientific nutrition advisory committees
59 confirmed the validity of dietary guidelines to reduce SFA, by their replacement with
60 unsaturated fatty acids [6, 7], particularly polyunsaturated fatty acids (PUFA), in part, on the
61 strength of the effect of this dietary change in lowering serum LDL-cholesterol (LDL-C). While
62 debate over the validity of this recommendation was positive in reinforcing its relevance to
63 human health, it also exposed weaknesses in the evidence for the impact of SFA on ASCVD,
64 and urgent need for a better understanding of the complex relationship between SFA and
65 serum LDL. The latter included gaining further insight into the effects of the specific
66 macronutrient which replaces SFA in the diet, SFA in whole foods and dietary patterns [8], and
67 impact of inter-individual variation in the response of serum LDL to the reduction of SFA. The
68 following narrative review examines the evidence for the origins of this variation in serum LDL-
69 C, and its potential contribution to the controversy over fat quality and ASCVD. Emphasis has
70 been placed on metabolic rather genetic determinants of this phenomenon, in areas where
71 the evidence is sufficiently robust to be appraised. The roles of obesity and related conditions
72 of insulin resistance in different genders and ethnic groups, while important, especially to the
73 cardiometabolic origins of variance in LDL, were considered to lie beyond the scope of the
74 review.

75

77 2. LDL cholesterol, apo B, and models of cholesterol homeostasis

78 The concentration of serum LDL is most commonly represented by its cholesterol content
79 ('LDL-C') but can also be expressed in terms of its total lipid and protein mass, or
80 concentration of its main structural protein, apoprotein B (apo B-100). Since each LDL particle
81 carries a single polypeptide chain of apo B-100, this protein conveys information about the
82 number of LDL particles. While both total serum cholesterol and apo B are informative with
83 respect to the association between LDL and cardiovascular risk, the most recent guidelines
84 from the European Cardiovascular Society and EAS, report that serum apo B provides the most
85 accurate marker of ASCVD, by providing a measure of the total number of atherogenic
86 lipoproteins in serum [9]. Moreover, serum apo B can be measured directly, inexpensively,
87 and with greater accuracy and precision than LDL-C, which is mostly calculated indirectly from
88 the Friedewald equation [10]. While these advantages confer greater all-round clinical utility
89 upon serum apo B [11, 12], LDL-C has remained the primary target for lipid-lowering drug
90 therapy, in part, because of its relatively greater prominence in the mechanism to explain the
91 regulation of serum LDL and whole-body cholesterol homeostasis [13]. The lowering of serum
92 LDL-C is also the main target for the dietary management of ASCVD risk, by approaches such
93 as the Portfolio Diet [14], though subtle differences exist between this approach and the
94 dietary management of elevated serum apo B [15].

95 The widely accepted view of serum LDL is that it provides cells with an available source of
96 cholesterol, the uptake of which requires less energy than cholesterol biosynthesis. This view
97 is supported by a model of cholesterol homeostasis, whereby the cellular uptake of LDL is
98 regulated by the expression and activity of cell surface LDL-receptors, the gene-transcription
99 of which is regulated by the amount of intra-cellular free cholesterol [13]. The size of the intra-
100 cellular pool of free cholesterol is governed by the rate of cholesterol biosynthesis, export of
101 cholesterol from the liver as bile acids and free cholesterol in bile, reabsorption of these bile
102 acids and cholesterol in the gut, and uptake of serum LDL by LDL-receptors. Cholesterol
103 biosynthesis co-ordinates with these other processes in a reciprocal fashion, to maintain a
104 mass of intra-cellular cholesterol that is appropriate for the requirement of cells, and, at the
105 same time, regulates and concentration of serum LDL [13]. However, because this traditional
106 model was largely developed in fibroblasts *in vitro*, it does not reflect the complexity of

cholesterol homeostasis *in vivo* [16]. In a mutually inclusive update of this conventional model, it has been proposed that cholesterol entering the liver in LDL, HDL or chylomicrons has different fates. In this updated model, LDL-derived cholesterol is largely shunted into the production of VLDL, without influencing the regulatory pool of intra-cellular cholesterol or expression of LDL-receptors, and HDL-derived cholesterol is incorporated into the production of bile acids. Most critically, it is the uptake of cholesterol into the liver in chylomicrons, and presumably their remnants, that enters the regulatory pool of intra-cellular cholesterol, and therefore is chiefly responsible for suppressing the activity of LDL-receptors [16]. This latter pathway has major implications for the metabolic coupling of serum LDL and triacylglycerol-rich lipoproteins and their remnants, and atherogenic roles of these lipoproteins in ASCVD.

3. Influence of dietary fatty acids on serum LDL-C; fundamental importance of macronutrient replacement

Arguably the strongest evidence to support dietary SFA as a modulator of total serum cholesterol, comes from tightly controlled, metabolic ward studies in the early 1950s, in which total serum cholesterol was manipulated by altering the relative proportions of dietary SFA and unsaturated fatty acids, from animal and plant sources, within milk shakes [17-19]. These findings were later supported by the outcome of epidemiological studies of Ancel Keys [20, 21], which laid the foundation for the 'diet-heart hypothesis' and earliest guideline to reduce intake of total fat and SFA to prevent heart attacks in the USA in 1961 [22]. Further evidence for the efficacy for this hypothesis would follow from randomised intervention trials (RCT) [23-25], and the most comprehensive meta-analysis to date of RCTs, that showed a 27% reduction in cardiovascular events in response to the replacement of SFA with polyunsaturated fat [26].

A fundamental principle that distinguishes the relatively subtle physiological effects of diet from the pharmacological effects of drugs, is the obligation to replace a removed macronutrient with a substitute macronutrient to render the diet viable. In the case of SFA, the substitute macronutrients of choice are either unsaturated fatty acids (PUFA or MUFA), carbohydrates or proteins. The replacement of SFA with unsaturated fats or carbohydrates have been shown to reduce serum LDL-C, in a dose-response fashion, with contributions to these effects coming from both the removal of SFA, and the type and quality of substitute

macronutrient [27]. Isocaloric replacement of 1% energy from dietary SFA with PUFA, chiefly in the form of linoleic acid, has been shown to be more effective in lowering serum LDL-C (mean change -0.055, 95% CI -0.061 to -0.050 mmol/L $P < 0.001$) than the equivalent replacement of SFA with either MUFA (mean change -0.042 mmol/L, 95% CI -0.047 to 0.037 mmol/L, $P < 0.001$) or carbohydrate (mean change -0.033, 95% CI -0.039 to -0.027 mmol/L, $P < 0.001$) [28]. Nevertheless, increased demand for low fat diets and food products has invariably favoured the replacement of SFA with carbohydrate in preference to unsaturated fat in the USA and UK. The latter dietary exchange is estimated to be associated with an unfavourable increase in serum triacylglycerol (mean change 0.011, 95% CI 0.007 to 0.014 mmol/L, $P < 0.001$) [28], and raises the significance of carbohydrate quality, specifically in relation to the opposing effects of dietary fibre and free sugars on serum triacylglycerol and other cardiometabolic risk factors.

Other relevant dietary sources of variation in serum LDL-C, include the effects of specific dietary fatty acids of variable chain length and capacity to raise and lower serum LDL-C [29], and other constituents in whole foods (e.g. minerals, food matrix), meals, and dietary patterns [30], which can alter the bioavailability and exposure to dietary SFA.

4. Evidence for variation in serum LDL-C in response to dietary cholesterol and SFA

Serum LDL-cholesterol varies within (intra) and between (inter) individuals in response to intrinsic factors (e.g. polymorphism and expression of genes, hormones) and extrinsic factors (e.g. diet, behaviour), and interactions between the two. Estimates for the proportion of inter-individual variation in serum LDL-C that can be ascribed to genetic heritability in and between populations, though wide ranging (20-90%) [31], still accommodates a significant contribution from environmental factors, including diet and nutrient-gene interactions.

The first reports of hyper and hypo-responsiveness of serum LDL to diet were in response to variable amounts of dietary cholesterol from eggs [32, 33]. This variation was not an acute artefact of the experimental design or due to variation in dietary compliance, but a reproducible phenomenon that would manifest in response to a second exposure to the same diet [34, 35]. It was established that dietary cholesterol and SFA exert additive, and even synergistic effects on serum LDL-C, but also that dietary cholesterol could exert its effects on LDL in the absence of SFA. Hyper and hypo-responsiveness in serum LDL-C was described as

differing degrees of change at either end of a continuous spectrum of responses to dietary cholesterol, rather than two discrete distributions or phenotypes [36]. In retrospect, the latter would be unlikely in view of the multiple genes and metabolic variables contributing to inter-individual variation.

The most well documented example of inter-individual variation in serum LDL-C in response to a reduced intake of SFA in men and women, comes from the effects of the US National Cholesterol Education Programme's (NCEP) Step 2 diet [37]. Low in total fat (18-29% energy) and SFA (4-7% energy), the Step 2 diet has been shown to produce dramatic reductions in serum LDL-C and significant variation between individuals. Exposure to this diet from between 4.5-24 weeks was reported to produce changes in serum LDL-C ranging from +3 to -55% and +13 to -39% in men and women, respectively. In this case, 48% of this variation could be accounted for by baseline LDL-C concentration and age in men, and 13% to age in women (**Figure 1A**). After taking into consideration variation in dietary compliance, and controlling for this and other extrinsic factors, significant variation was attributed to apo E genotype. Significant variation in serum LDL-C has also been observed in response to an increased intake of SFA in two randomised controlled intervention studies; 'Dietary fat & VAScular function' 'DIVAS' study, **Figure 1(B)**, and 'Reading, Imperial, Surrey, Cambridge & Kings' ('RISCK') study' [38, 39]. Rigorous control of confounding, extrinsic factors and dietary compliance in these studies, provided further evidence to suggest that the variation in serum LDL-C originated from intrinsic biological differences in the metabolic handling and impact of dietary SFA on cholesterol homeostasis between individuals.

5. Origins of variation in serum LDL-C in response to diet and SFA

5.1 Confounding influences of inter and intra-variation in serum LDL-C

Dietary guidelines to reduce disease risk are primarily designed for human populations that show inherent variability in risk susceptibility, dietary compliance, and response to dietary recommendations. When variation in an outcome measure (serum LDL-C) in response to an intervention (replacement of dietary SFA) is greater between individuals than the average response of the study population, this will reduce the ability of that study to demonstrate a significant effect of the intervention on that outcome measure. It is evident in each of the studies shown in **Figures 1 (A) & (B)** that the magnitude of inter-individual variation in response to SFA intake is greater than the mean response, which will effectively

reduce the significance of the dietary intervention [40]. Similarly, the amount of error and ability to demonstrate a significant association between two variables depends on the ratio of the intra to inter-variability in these variables. If intra-variation is greater than the inter-individual variation, this will attenuate the strength of association between the two variables [41]. While this has been reported to apply to the association between serum LDL-C and dietary SFA, this is not supported by observations of inter and intra-variation in LDL-C in response to diet. A comparison of inter and intra-individual variation in total serum cholesterol in 58 men, on six different dietary regimens for between 3-10 weeks, showed that inter-individual variation (between men) was nearly two-fold greater than variation within these men [42] (**Figure 2**). Irrespective of this difference, it is likely that both inter- and intra-variation will attenuate the strength of associations between LDL-C, SFA and CVD, and reduce the strength of the statistical evidence on which dietary recommendations are based, even within dietary compliant cohorts. Identification of this variation in LDL response to SFA, together with an increased understanding of the metabolic origins of these traits, would provide the opportunity to tailor dietary recommendations to serum LDL-C-responsiveness, to enhance the effects of this dietary change in a more personalised dietary approach.

5.2 Mechanistic insights from the effects of dietary cholesterol in metabolic studies

The human liver and gut work in concert to regulate the rates of endogenous cholesterol synthesis and absorption, through a reciprocal mechanism that suppresses cholesterol synthesis in the liver in response to increased cholesterol absorption in the gut, and vice versa. This mechanism is largely driven by the inter-connecting entero-hepatic circulation that produces and reabsorbs bile acids (and biliary cholesterol) to facilitate the absorption of dietary fat and cholesterol [43]. As discussed previously, the reciprocal relationship between the absorption of dietary cholesterol, and biosynthesis of cholesterol, chiefly in the liver, effectively controls the amount of free cholesterol (FC) within cells, which ultimately regulates the concentration of serum LDL-C by adjusting the uptake of LDL into cells via membrane LDL receptors. Expression of LDL-receptors is governed by a mechanism of inhibition feedback that modulates the transcription of the LDL-receptor gene by 'sensing' the level of intra-cellular free cholesterol. This mechanism also forms the basis of our understanding of the differential effects of dietary fatty acids on serum LDL-C, mediated through differences in the

esterification of intra-cellular cholesterol, as described in the pioneering work of John Dietschy [44, 45].

While it is often assumed that the ‘push-pull’ reciprocity between cholesterol biosynthesis and absorption is finely attuned, there exists the possibility for inter-individual variability in the magnitude to which these variables can respond to each other and become misaligned. Imbalance in these processes would manifest as distinct metabolic phenotypes or ‘metabotypes’ characterised by either higher cholesterol synthesis (low absorption) or higher absorption (low synthesis). Evidence from metabolic studies for the existence of such metabotypes, who are respectively less and more sensitive to dietary cholesterol, may underlie the phenomenon of hypo and hyper-responsiveness of serum LDL-C to dietary cholesterol, which may, in part, be an inherited trait [46]. The relatively greater efficacy of LDL-lowering drugs that either inhibit cholesterol synthesis or block absorption in the gut (e.g. statins and ezetimibe) in synthesisers or absorbers of cholesterol, respectively, provides further evidence for the existence of these discrete metabotypes [47, 48]. Factors governing the absorption and synthesis of cholesterol are summarised in **Figure 3**.

5.3 Key role of bile acids in the absorption of dietary SFA and cholesterol

The additive and even synergistic effects of dietary SFA and dietary cholesterol on serum LDL-C, reflect the fact that these dietary lipids share common determinants of cholesterol homeostasis. While congruence in the response of serum LDL-C response to these dietary components may be helpful in explaining the origins of variation in serum LDL-C to dietary SFA [49], dietary fatty acids and cholesterol are absorbed by different mechanisms. The bulk of dietary SFA (98%) is absorbed in the upper jejunum, whereas about 50% of cholesterol in the gut lumen is absorbed throughout the small intestine, via a series of regulatory transport proteins. However, since the absorption of both dietary lipids depends on the production and resorption of bile salts in the entero-hepatic circulation, the metabolism of bile acids provides a credible link between dietary SFA, cholesterol synthesis and absorption [47], which could help to explain variation in LDL-C response to SFA.

Bile acids are the products of metabolic events occurring primarily between the liver and gut microbiota. Primary bile acids are synthesised in the liver from cholesterol and conjugated with either taurine or glycine to form bile salts, which are stored in the gall bladder and

secreted into the bile. This conjugation step enhances bi-polarity, which increases the capacity of bile acids to emulsify dietary fat for absorption. Conversely, bacterial bile salt hydrolases (BSH) deconjugate primary bile salts in the gut, reducing their efficiency to emulsify dietary fat [50, 51]. The circulating bile acid pool contains more than 30 known bile acids, the diversity of which is largely driven by the gut microbiota. In addition to facilitating fat absorption, bile acid production drives the flow of bile. Bile acids also act as key cell signalling molecules, which serve as ligands for nuclear receptors that regulate the transcription of genes involved in lipid metabolism [52-54]. The gut microbiota shares a bi-directional relationship with dietary fat, by influencing the absorption of fat through bile salts, and, in turn, being modified by dietary fat. The BSH activity of certain bile acid-deconjugating lactobacilli and bifidobacteria may be especially relevant in the former respect, by reducing the absorption of dietary fat and lowering serum LDL-C, as shown in human intervention studies with probiotics [55]. The microbiota may also influence the effects of dietary SFA on serum LDL-C through the production of short chain fatty acids (SCFA) [56]. Acetate and propionate have been shown to stimulate and inhibit cholesterol biosynthesis, respectively. Propionate may also inhibit the uptake of acetate into hepatocytes, thus producing downstream effects on cholesterol metabolism. In this respect, a high SFA diet has been reported to increase the excretion of SCFA, which attenuated the significant reduction in serum LDL-C when switching to a low SFA diet [56].

5.4 Relevance of LDL particle size distribution and subclass phenotype

In keeping with the other main classes of serum lipoproteins, LDL shows structural and metabolic heterogeneity and exists as a variable number of discrete LDL subclasses [57]. When characterised and quantified by their hydrated density, particle size, and unique magnetic signatures, LDL subfractions express a gradient of increasing atherogenic potential on moving from large, buoyant LDL, to small, dense LDL [5, 58].

Dietary SFA have been reported to act primarily on larger LDL particles [59, 60], and since larger LDL is associated with lower ASCVD risk, this idea has been invoked to explain the lack of evidence for a direct link between SFA and ASCVD. A potential flaw in this idea lies in the fact that if larger LDL were unrelated to CVD risk, this would tend to negate the positive risk

association between serum LDL-C and ASCVD in populations, since for most people without a predominance of small, dense LDL, the bulk of LDL mass will reside in 'larger' cholesterol-rich subfractions. Mechanistically, there is evidence to suggest that larger LDL express a higher affinity for LDL-receptors than smaller, dense LDL [61]. As such, the effect of adding or replacing dietary SFA on LDL-receptor activity should be to selectively increase or decrease larger LDL, respectively. However, this may not be the case if the uptake of cholesterol from LDL has a minimal effect in regulating intra-free cholesterol and production of LDL receptors *in vivo*. It could also be off-set by the nature of substitute macronutrient, with refined carbohydrate producing the opposite effect to SFA on large LDL [59]. Understanding how LDL particle size influences the effect of SFA replacement on serum LDL-C, and LDL particle number (LDL-apo B), has been difficult to establish, and may depend on the initial distribution of LDL particle size (LDL subclass phenotype), dietary exchanges, and threshold effects of SFA intake [62].

5.5 Genetic polymorphism in apoprotein E

Numerous common single nucleotide polymorphisms have been reported to influence the response of serum LDL-C to dietary fats, the address of which lies beyond the scope of this review [63-71]. Of all common genetic traits studied to date, two missense single nucleotide polymorphisms in the apoprotein E gene (rs429358 and rs7412 at codons 112 and 158, respectively) are by far the most well documented in relation to variance in serum LDL-C and diet. These polymorphisms produce different isoforms of apoprotein E with variable capacity to function as ligands for the binding of triacylglycerol-rich lipoproteins and their remnants, and HDL, to cell surface receptors, including LDL receptors. They are reported to account for up to 8-10% of variance in serum LDL-C in populations [72], primarily, by influencing the regulatory pool of intra-cellular free cholesterol and activity of LDL-receptors, as described previously. Apo E polymorphism has also been linked to variation in serum LDL-C response to changes in dietary SFA and cholesterol [73, 74]. Most notably, carriers of the $\epsilon 4$ allele (apo E4 isoform) tend to have elevated serum LDL-C (5-10%) and are consistently more responsive to changes in SFA, primarily because of the common pathways by which dietary SFA, and to a lesser extent, dietary cholesterol elevate serum LDL-C by modulating intra-cellular cholesterol and the expression of LDL receptors. Carriage of the apo E4 variant has also been shown to be

more effective in lowering serum LDL-C and apo B than wild type (E3/E3), when SFA is replaced with low glycaemic index carbohydrates [75].

6. Future perspectives and conclusions

The cardiovascular risk that can be attributed to elevated serum LDL-C in a population is a function of the absolute risk (mortality associated with the concentration of raised LDL-C over a prospective follow-up period), and number of people with that level of serum LDL-C.

Moderately elevated serum cholesterol is extremely common in populations, but carries a relatively low absolute risk in comparison to some other risk factors, such as blood pressure, making both total serum cholesterol and LDL-C poor discriminators of ASCVD risk within populations. Inter-individual variation in disease risk associated with elevated serum LDL-C and its variable response to treatment, including diet, will contribute to this low absolute risk. As such, a serum biomarker of serum LDL-C responsiveness to the replacement of dietary SFA would have major utility in increasing the power to discriminate disease risk, in this otherwise diagnostically grey area.

While the impact of replacing SFA on serum LDL-C is considerably less than can be achieved with lipid-lowering drugs, the combination of several dietary bio-actives for LDL-lowering within dietary patterns, such as the Portfolio [13] and Mediterranean diets [76], can reduce serum LDL-C by up to 30%. In this context, the identification of serum LDL-C responsive individuals would increase efficacy, by the targeting of dietary advice to LDL-responsive individuals who stand to gain the most benefit.

In conclusion, the answer to the question 'Does variation in serum LDL-cholesterol response to dietary fatty acids help in explaining the controversy over fat quality and cardiovascular disease risk?' is likely to be 'yes', since this variation, together with its genetic and metabolic origins, will attenuate the strength of statistical associations between LDL-C, SFA and ASCVD.

References

- [1] D. Steinberg, An interpretive history of the cholesterol controversy, part II: the early evidence linking hypercholesterolemia to coronary disease in humans, *J Lipid Res* 46 (2005) 179-190.
- [2] Z. Harcombe, J.S. Baker, J.J. DiNicolantonio, F. Grace, B. Davies, Evidence from randomised controlled trials does not support current dietary fat guidelines: a systematic review and meta-analysis, *Open Heart* 3 (2016) e000409.
- [3] J.L. Heilsen, Dietary saturated fat and heart disease: a narrative review, *Nutr Rev* 78 (2020) 474-485.
- [4] B.A. Ference, H.N. Ginsberg, I. Graham, K.K. Ray, C.J. Packard, Bruckert E, et al., Low-density lipoproteins cause atherosclerotic cardiovascular disease. 1. Evidence from genetic, epidemiologic, and clinical studies. A consensus statement from the European Atherosclerosis Society Consensus Panel, *Eur Heart J* 38 (2017) 2459-2472.
- [5] J. Boren, M.J. Chapman, R.M. Krauss, C.J. Packard, J.F. Bentzon, C.J. Binder et al., Low-density lipoproteins cause atherosclerotic cardiovascular disease: pathophysiological, genetic, and therapeutic insights: a consensus statement from the European Atherosclerosis Society Consensus Panel, *Eur Heart J* 41, (2020) 2313-2330.
- [6] World Health Organization. Draft guidelines on saturated fatty acid and trans-fatty acid intake for adults and children. Public Consultation May to June 2018. [https://extranet.who.int/dataform/upload/surveys/666752/files/Draft%20WHO%20SFA-TFA%20guidelines_04052018%20Public%20Consultation\(1\).pdf](https://extranet.who.int/dataform/upload/surveys/666752/files/Draft%20WHO%20SFA-TFA%20guidelines_04052018%20Public%20Consultation(1).pdf)

378

379 [7] The Scientific Advisory Committee on Nutrition (SACN) report on saturated fats and
380 health, (2019) [https://www.gov.uk/government/publications/saturated-fats-and-health-](https://www.gov.uk/government/publications/saturated-fats-and-health-sacn-report)
381 [sacn-report](https://www.gov.uk/government/publications/saturated-fats-and-health-sacn-report). (Accessed 20/11/2020).

382

383 [8] A. Astrup, H.C.S. Bertram, J.P. Bonjour, L.C.P. de Groot, M.C.O. Otto, E.L. Feeney et al.,
384 WHO draft guidelines on dietary saturated and trans fatty acids: time for a new approach?
385 Brit Med J 366 (2019) l4137.

386

387 [9] F. Mach, C. Baigent, A.L. Catapano, K.C. Koskinas, M. Casula, L. Badimon et al., ESC/EAS
388 Guidelines for the management of dyslipidaemias: lipid modification to reduce
389 cardiovascular risk. Eur Heart J 41 (2020) (2019) 111-188.

390

391 [10] W.T Friedewald, R.I. Levy, D.S. Fredrickson, Estimation of the concentration of low-density
392 lipoprotein cholesterol in plasma, without use of the preparative ultracentrifuge, *Clin Chem*
393 18, (1972) 499-502.

394

395 [11] C.N. Kohli-Lynch, G. Thanassoulis, A.E. Moran, A.D. Sniderman, The clinical utility of apoB
396 versus LDL-C/non-HDL-C, *Clin Chim Acta* 508, (2020) 103-108.

397

398 [12] A.D. Sniderman, Did theACC/AHA/AACVPR/AAPA/ABC/ACPM/ADA/AGS/APhA/ASPC/NLA
399 /PCNA cholesterol guidelines get apo B right?, *J Clin Lipidol* 13 (2019) 360-336.

400

401 [13] M.S. Brown, J.L. Goldstein, A receptor-mediated pathway for cholesterol homeostasis,
402 Science 232 (1986) 34-47.

403

404 [14] L. Chiavaroli, S.K. Nishi, T.A. Khan, C.R. Braunstein, A.J. Glenn, S.B. Mejia, et al.,
 405 Portfolio dietary pattern and cardiovascular disease: A systematic review and meta-
 406 analysis of controlled trials, *Prog Cardiovasc Dis* 61 (2018) 43-53.

407

408 [15] V. Lamantia, A.D. Sniderman, M. Faraj, Nutritional Management of hyperapoB, *Nutr Res*
 409 *Rev* 29 (2016) 202-233,

410

411 [16] R.S. Kiss, A.D. Sniderman, Shunts, channels and lipoprotein endosomal traffic: a new model
 412 of cholesterol homeostasis in the hepatocyte, *J Biomed Res* 31 (2017) 95-107.

413

414 [17] L.W. Kinsell, J. Partridge, L. Boling, S. Margen, G. Michael, Dietary modification of serum
 415 cholesterol and phospholipid levels, *J Clin Endocrinol Metab* 12 (1952) 909-913.

416

417 [18] E.H. Ahrens Jr., D.H. Blankenhorn, T.T. Tsaltas, Effect on human serum lipids of substituting
 418 plant for animal fat in diet, *Proc Soc Exp Biol Med* 86 (1954) 872-878.

419

420 [19] R. Clarke, C. Frost, R. Collins, P. Appleby, R. Peto, Dietary lipids and blood cholesterol:
 421 quantitative meta-analysis of metabolic ward studies, *Brit Med J* 314 (1997) 112-117.

422

423 [20] A. Keys, J.T. Anderson, F. Grande, Serum cholesterol in man: diet fat and intrinsic
 424 responsiveness, *Circulation* 19 (1959) 201-214.

425

426 [21] A. Keys, J.T. Anderson, F. Grande, Serum cholesterol response to changes in diet. IV.
 427 Particular saturated fatty acids in the diet, *Metabolism* 14 (1965) 776-787.

428

429 [22] Report of the Committee for Medical and Community Program of the American Heart
 430 Association, Dietary Fat and Its Relation to Heart Attacks and Strokes, *Circulation* 23 (1961)
 431 133-136.

432

433 [23] P. Leren, The effect of plasma cholesterol lowering diet in male survivors of myocardial
 434 infarction. A controlled clinical trial, *Acta Med Scand* 466 (Suppl) (1966) 1-92.

435

436 [24] S. Dayton, M.L. Pearce, H. Goldman, A. Harnish, D. Plotkin, M. Shickman, et al., Controlled
 437 trial of a diet high in unsaturated fat for prevention of atherosclerotic complications, *Lancet*
 438 2 (1968) 1060-1062.

439

440 [25] M. Miettinen, O. Turpeinen, M.J. Karvonen, R. Elosuo, E. Paavilainen, Effect of cholesterol-
 441 lowering diet on mortality from coronary heart disease and other causes. A twelve-year
 442 clinical trial in men and women, *Lancet* 2 (1972) 835-838.

443

444 [26] L. Hooper, N. Martin, A. Abdelhamid, G.D. Smith, Reduction in saturated fat intake for
 445 cardiovascular disease. *Cochrane Database System Review*, 101 (2015) 1938-1940.

446

447 [27] R. Micha, D. Mozaffarian, Saturated fat and cardiometabolic risk factors, coronary heart
 448 disease, stroke, and diabetes: a fresh look at the evidence, *Lipids* 45 (2010) 893-905.

449

450 [28] R.P. Mensink, Effects of saturated fatty acids on serum lipids and lipoproteins: a
 451 systematic review and regression analysis, Geneva: World Health Organization; 2016.
 452 <https://apps.who.int/iris/bitstream/handle/10665/246104/9789241565349-eng.pdf>

453

454 [29] R.P. Mensink, P.L. Zock, A.D.M. Kester, M.B. Katan, Effects of dietary fatty acids and
 455 carbohydrates on the ratio of serum total to HDL cholesterol and on serum lipids and
 456 apolipoproteins: a meta-analysis of 60 controlled trials, *Am J Clin Nutr* 77 (2003) 1146-
 457 1155.

458

459 [30] A. Astrup, F. Magkos, D.M. Bier, J.T. Brenna, M.C.de Oliveira Otto, J.O. Hill, Saturated fats
 460 and health: A reassessment and proposal for food-based recommendations, *J Am Col*
 461 *Cardiol* 76, (2020) 844-857.

462

463 [31] G. Jermendy, T. Horváth, L. Littvay, R. Steinbach, Á. L. Jermendy, Á.D. Tárnoki et al., Effect
 464 of genetic and environmental influences on cardiometabolic risk factors: a twin study,
 465 *Cardiovas Diabetol* 10 (2011) 96.

466

467 [32] A.C. Beynen, M.B. Katan, Inter-individual variation in the cholesterolemic response to
 468 dietary cholesterol, *Prog Clin Biol Res* 188 (1985) 195-207.

469

470 [33] M.B. Katan, A.C. Beynen, J.H. de Vries, A. Nobels, Existence of consistent hypo- and hyper-
 471 responders to dietary cholesterol in man, *Am J Epidemiol* 123 (1986) 221-234.

472

473 [34] A.C. Beynen, M.B. Katan, L.F. Van Zutphen, Hypo- and hyperresponders: individual
 474 differences in the response of serum cholesterol concentration to changes in diet, *Adv*
 475 *Lipid Res* 22, (1987) 115-171.

476

477 [35] C. Cox, J. Mann, W. Sutherland, M. Ball, Individual variation in plasma cholesterol response
 478 to dietary saturated fat, *Brit Med J* 311 (1995) 1260-1264.

479

480 [36] A.J. Wallace, J.I. Mann, W.H. Sutherland, S. Williams, A. Chisholm, C.M. Skeaff, Variation in
 481 plasma cholesterol response to dietary change, *Nutr Metab Cardiovasc Dis* 9 (1999) 176-
 482 183.

483

- 484 [37] E.J. Schaefer, S. Lamon-Fava, L.M. Ausman, J.M. Ordovas, B.A. Clevidence, J.T. Judd, et al.,
485 Individual variability in lipoprotein cholesterol response to National Cholesterol Education
486 Program Step 2 diets, *Am J Clin Nutr* 65 (1997) 823-830.
- 487
488
- 489 [38] K. Vafeiadou, M. Weech, H. Altowaijri, S. Todd, P. Yaqoob, K.G. Jackson, et al.,
490 Replacement of saturated with unsaturated fats had no impact on vascular function but
491 beneficial effects on lipid biomarkers, E-selectin, and blood pressure: results from the
492 randomized, controlled Dietary Intervention and VAScular function (DIVAS) study, *Am J Clin*
493 *Nutr* 102 (2015) 40-48.
- 494
- 495 [39] S.A. Jebb, J.A. Lovegrove, B.A. Griffin, G.S. Frost, C.S. Moore, M.D. Chatfield MD, et al.,
496 Effect of changing the amount and type of fat and carbohydrate on insulin sensitivity
497 and cardiovascular risk: the RISCK (Reading, Imperial, Surrey, Cambridge, and Kings)
498 Trial, *Am J Clin Nutr* 92 (2010) 748-758.
- 499
- 500 [40] D.R. Jacobs, Jr., J.T. Anderson, H. Blackburn, Diet and serum cholesterol - do zero
501 correlations negate the relationship?, *Am J Epidemiol* 110 (1979) 77-78.
- 502
- 503 [41] D. Kromhout, J.M. Geleijnse, A. Menotti, D.R. Jacobs Jr., The confusion about dietary fatty
504 acids recommendations for CHD prevention, *Brit J Nutr* 106 (2011) 627-663.
- 505
- 506 [42] D.R. Jacobs, Jr., J.T. Anderson, P. Hannan, A. Keys, H. Blackburn, Variability in individual
507 serum cholesterol response to change in diet, *Arteriosclerosis* 3 (1983) 349-356.
- 508
- 509 [43] P.A.S. Alphonse, P.J.H. Jones, Revisiting human cholesterol synthesis and absorption: The
510 reciprocity paradigm and its key regulator, *Lipids* 51 (2016) 519-536.
- 511

- [44] J.M. Dietschy, L.A. Woollett, D.K. Spady, The interaction of dietary cholesterol and specific fatty acids in the regulation of LDL receptor activity and plasma LDL-cholesterol concentrations, *Ann N Y Acad Sci.* 676 (1993) 11-26.
- [45] J.M. Dietschy, Dietary Fatty Acids and the Regulation of Plasma Low Density Lipoprotein Cholesterol Concentrations, *J Nutr* 128 (1998)444S-448S.
- [46] H. Gylling, T.A. Miettinen, Inheritance of cholesterol metabolism of probands with high or low cholesterol absorption, *J Lipid Res* 43 (2002) 1472-1476.
- [47] S. Santosa, K.A. Varady, S. AbuMweis, P.J. Jones, Physiological and therapeutic factors affecting cholesterol metabolism: does a reciprocal relationship between cholesterol absorption and synthesis really exist?, *Life Sci* 80 (2007) 505-514.
- [48] P.E. Ziajka , M. Reis, S. Kreul, H. King, Initial low-density lipoprotein response to statin therapy predicts subsequent low-density lipoprotein response to the addition of ezetimibe, *Am J Cardiol* 93 (2004) 779-780.
- [49] M.B. Katan, M.A.M. Berns, J.F.C. Glatz, J.T.Knuiman, A. Nobels, J.H.M. de Vries, Congruence of individual responsiveness to dietary cholesterol and to saturated fat in humans, *J Lipid Res* 29 (1988) 883-892.
- [50] M.D. Wilson, L.L Rudel, Review of cholesterol absorption with emphasis on dietary and biliary cholesterol, *J Lipid Res* 35 (1994) 943-955.
- [51] J.Y.L. Chian, Bile Acid Metabolism and Signaling, *Compr Physiol.* 2013 3 (2013) 1191-1212.
- [52] G. Musso, R. Gambino, M. Cassader, Interactions between gut microbiota and host metabolism predisposing to obesity and diabetes, *Annu Rev Med* 62 (2011) 361-380.

- [53] J.R. Swann, E. J. Want, F.M. Geier, K. Spagou, I.D. Wilson, J.E. Sidaway, et al., Systemic gut microbial modulation of bile acid metabolism in host tissue compartments, *Proc Natl Acad Sci USA* 108 Suppl 1 (2011) 4523-4530.
- [54] G. Porez, J. Prawitt, B. Gross, B. Staels, Bile acid receptors as targets for the treatment of dyslipidemia and cardiovascular disease, *J Lipid Res* 53 (2012) 1723-1737.
- [55] M.L. Jones, C.J. Martoni, M. Parent, S. Prakash, Cholesterol-lowering efficacy of a microencapsulated bile salt hydrolase-active *Lactobacillus reuteri* NCIMB 30242 yoghurt formulation in hypercholesterolaemic adults *Br J Nutr* 107 (2012) 1505-1513.
- [56] C. Demigné, C. Morand, M.A. Levrat, C. Besson, C. Moundras, C. Rémésy, Effect of propionate on fatty acid and cholesterol synthesis and on acetate metabolism in isolated rat hepatocytes, *Br J Nutr* 74 (1995) 209-219.
- [57] B.A. Griffin, Low-density lipoprotein heterogeneity, *Baillière's Clin Endo Metab* 9 (1995) 687-703.
- [58] R.M. Krauss, Lipoprotein subfractions and cardiovascular disease risk, *Curr Op Lipidol* 21 (2010), 305-311.
- [59] D.M. Dreon, H.A. Fernstrom, H. Campos, P. Blanche, P.T. Williams, R.M. Krauss, Change in dietary saturated fat intake is correlated with change in mass of large low-density-lipoprotein particles in men, *Am J Clin Nutr* 67 (1998) 828-836.
- [60] M. Yuan, R.T. Pickering, M. Singer, L. Moore, Dietary Saturated Fat Is Associated with Larger LDL Particle Size and Reduced CVD Risk in Framingham Offspring Study, *Curr Develop Nutr* 3 Suppl 1 (2019) 128-119.

570

571 [61] S. Lund-Katz, P.M. Laplaud, M.C. Phillips, M.J. Chapman Apolipoprotein B-100
572 conformation and particle surface charge in human LDL subspecies: implication for LDL
573 receptor interaction Biochem, 37 (1998) 12867-12874.

574

575 [62] S. Chiu, P.T. Williams, R.M. Krauss, Effects of a very high saturated fat diet on LDL
576 particles in adults with atherogenic dyslipidemia: A randomized controlled trial, PLoS ONE
577 12 (2017) e0170664.

578

579 [63] H. Gylling, M. Hallikainen, J. Pihlajamäki, J. Agren, M. Laakso, R.A. Rajaratnam, et al.,
580 Polymorphisms in the ABCG5 and ABCG8 genes associate with cholesterol absorption and
581 insulin sensitivity, J Lipid Res 45 (2004) 1660-1665.

582

583 [64] S. Santosa, I. Demonty, A.H. Lichtenstein, J.M. Ordovas, P.J. Jones, Single nucleotide
584 polymorphisms in ABCG5 and ABCG8 are associated with changes in cholesterol
585 metabolism during weight loss. J Lipid Res 48 (2007) 2607-2613.

586

587 [65] J.M. Anderson, A. Cerda, M.H. Hirata, A.C. Rodrigues, E.L. Dorea, M.M. Bernik, et al.,
588 Influence of PCSK9 polymorphisms on plasma lipids and response to atorvastatin
589 treatment in Brazilian subjects, J Clin Lipidol 8 (2014) 256-64.

590

591 [66] A. Alsaleh, S.D. O'Dell, G.S. Frost, B.A. Griffin, J.A. Lovegrove, S.A. Jebb SA, et al., Single
592 nucleotide polymorphisms at the ADIPOQ gene locus interact with age and dietary intake
593 of fat to determine serum adiponectin in subjects at risk of the metabolic syndrome, Am J
594 Clin Nutr 94, 262-269.

595

596

597 [67] C.G. Walker, R.J. Loos, A.D. Olson, G.S. Frost, B.A. Griffin, J.A. Lovegrove, et al., Genetic
598 predisposition influences plasma lipids of participants on habitual diet, but not the
599 response to reductions in dietary intake of saturated fatty acids, *Atherosclerosis* 215, 421-
600 427.

601

602 [68] A. AlSaleh, S.D. O'Dell, G.S. Frost, B.A. Griffin, J.A. Lovegrove, S.A. Jebb, et al., Interaction
603 of *PPARG* Pro12Ala with dietary fat influences plasma lipids in subjects at cardiometabolic
604 risk, *J Lipid Res* 52, 2298-2303.

605

606 [69] U.S. Schwab, H.M. Maliranta, E.S. Sarkkinen, M. J. Savolainen, A. KesSniemi, M.I.J.
607 Uusitupa, Different Effects of Palmitic and Stearic Acid-Enriched Diets on Serum Lipids and
608 Lipoproteins and Plasma Cholesteryl Ester Transfer Protein Activity in Healthy Young
609 Women, *Metabolism* 45 (1996) 143-149.

610

611 [70] S. Jansen, J.López-Miranda, P. Castro, F. López-Segura, C. Marín, J.M. Ordovás, et al.,
612 Low-fat and high-monounsaturated fatty acid diets decrease plasma cholesterol ester
613 transfer protein concentrations in young, healthy, normolipemic men, *Am J Clin Nutr* 72
614 (2000) 36-41.

615

616 [71] A.J. Wallace, J.I. Mann, W.H.F. Sutherland, S. Williams, A. Chisholm, C.M. Skeaff, et al.,
617 Variants in the cholesterol ester transfer protein and lipoprotein lipase genes are
618 predictors of plasma cholesterol response to dietary change, *Atherosclerosis* 152 (2000)
619 327-333.

620

621 [72] P.W. Wilson, E.J. Schaefer, M.G. Larson, J.M. Ordovas, Apolipoprotein E alleles and risk of
622 coronary disease. A meta-analysis. *Arterioscler Thromb Vasc Biol* 16 (1996) 1250-1255.

623

624 [73] E. Sarkkinen, M. Korhonen, A. Erkkila, T. Ebeling, M. Uusitupa, Effect of apolipoprotein E
625 polymorphism on serum lipid response to the separate modification of dietary fat and
626 dietary cholesterol, *Am J Clin Nutr* 68 (1998) 1215-1222.

627

- [74] A. Minihane, L. Jofre-Monseny, E. Olano-Martin, G. Rimbach, Apo E genotype, cardiovascular risk and responsiveness to dietary fat manipulation, *Proc Nutr Soc* 66 (2207) 183-197.
- [75] B.A. Griffin, C.G. Walker, S.A. Jebb, C. Moore, G.S. Frost, L. Goff, et al., APOE4 Genotype exerts greater benefit in lowering plasma cholesterol and apolipoprotein B than wild type (E3/E3), after replacement of dietary saturated fats with low glycaemic index carbohydrates, *Nutrients* 10 (2018) 1524.
- [76] R.J Widmer, A.J. Flammer, L.O. Lerman, A. Lerman, The Mediterranean diet, its components, and cardiovascular disease, *Am J Med* 128 (2015) 229-238.

Legends to Figures

Figure 1 (A)

Individual variation in serum LDL-cholesterol in response to a high SFA diet ($17.6 \pm 0.4\%$ total energy (mean $\pm$ SEM) relative to habitual diet (SFA $11.5 \pm 0.5\%$ total energy) in men and women (n=65) at increased risk of CVD in the 'DIVAS' study. A mean increase in the intake of

SFA of 6.1% total energy produced variation in serum LDL-cholesterol ranging from +45 to -20%.
Data taken from [38].

Figure 1 (B)

Individual variation in serum LDL-cholesterol in response to a high SFA diet ($16.0 \pm 3.0\%$ total energy (mean $\pm$ SD) relative to habitual diet (SFA $13.0 \pm 3.5\%$ total energy) in men and women (n=69) at risk of developing metabolic syndrome in the 'RISCK' study. A mean increase in the intake of SFA of 3.0% total energy produced variation in serum LDL-cholesterol ranging from to +30 to -30%. Data taken from [39].

Figure 2

Frequency distribution of variation in serum cholesterol between individuals (inter) as compared within individuals (intra) in 58 metabolically healthy men, in response to six consecutive dietary interventions (data taken from Ref. [42]). The diets differed by the quality of a macronutrient supplement (28% total energy) e.g. exchange in dietary fats (SFA exchanged for PUFA) and carbohydrate (sugars exchanged with starch). For further details of diets see Ref. [42].

Figure 3

Control of serum LDL-cholesterol and LDL-receptor expression via the reciprocal 'push-pull' relationship between the intestinal absorption and whole body synthesis of cholesterol, with inputs from bile acid synthesis and excretion, and gut microbiota.