Targeting the gut microbiota with inulin-type fructans: preclinical demonstration of a novel approach in the management of endothelial dysfunction

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ABSTRACT

Objective To investigate the beneficial role of prebiotics on endothelial dysfunction, an early key marker of cardiovascular diseases, in an original mouse model linking steatosis and endothelial dysfunction.

Design We examined the contribution of the gut microbiota to vascular dysfunction observed in apolipoprotein E knockout (Apoe⁻/⁻) mice fed an n-3 polyunsaturated fatty acid (PUFA)-depleted diet for 12 weeks with or without inulin-type fructans (ITFs) supplementation for the last 15 days. Mesenteric and carotid arteries were isolated to evaluate endothelium-dependent relaxation ex vivo. Caecal microbiota composition (Illumina Sequencing of the 16S rRNA gene) and key pathways/mediators involved in the control of vascular function, including bile acid (BA) profiling, gut and liver key gene expression, nitric oxide and gut hormones production were also assessed.

Results ITF supplementation totally reverses endothelial dysfunction in mesenteric and carotid arteries of n-3 PUFA-depleted Apoe⁻/⁻ mice via activation of the nitric oxide (NO) synthase/NO pathway. Gut microbiota changes induced by prebiotic treatment consist in increased NO-producing bacteria, replenishment of abundance in Akkermansia and decreased abundance in bacterial taxa involved in secondary BA synthesis. Changes in gut and liver gene expression also occur upon ITFs suggesting increased glucagon-like peptide 1 production and BA turnover as drivers of endothelial function preservation.

Conclusions We demonstrate for the first time that ITF improve endothelial dysfunction, implicating a short-term adaptation of both gut microbiota and key gut peptides. If confirmed in humans, prebiotics could be proposed as a novel approach in the prevention of metabolic disorders-related cardiovascular diseases.

INTRODUCTION

Nutritional quality of diets underlies or exacerbates several chronic pathologies, including cardiovascular disease (CVD). Western diets that are mainly characterised by an imbalance between energy and fat intakes and a lack of key nutrients,
like fibres and n-3 polyunsaturated fatty acids (PUFAs), enhance CVD risk. An early key marker of CVD is endothelial dysfunction, reflecting the integrated effects of risk factors on the vasculature. It originates from the incapacity of endothelial cells to balance synthesis and release of deleterious versus protective mediators, among which nitric oxide (NO) is the most important. Endothelial dysfunction is characterised by reduced vasodilation in response to endothelial stimuli. Interestingly, besides inducing metabolic alterations, nutritional depletion in n-3 PUFAs for 12 weeks accelerates the process of endothelial dysfunction in apolipoprotein E knockout (Apo−/−) mice.

The gut microbiota comprises the trillions of commensal micro-organisms residing within our intestines. The gut microbiota is considered as an ‘external’ organ playing an important role in host physiology and metabolism. Only a few studies focus on the role of gut microbiota in the context of CVDs. Interestingly, Stepankova et al. reported that germ-free Apo−/− mice developed more aortic atherosclerotic plaques compared with conventionally raised Apo−/− mice fed the same low standard cholesterol diet. Rault-Nania et al. demonstrated that inulin treatment attenuated atherosclerosis in Apo−/− mice, however, the mechanism was unexplored. We found that inulintype fructans (ITFs) feeding increases the abundance of Akkermansia muciniphila in obese mice.

For years, we and others have proven that dietary fibre supplementation can modulate the composition of the gut microbiota, and thus interact with host physiology. This is particularly the case for ITFs, which are classified as prebiotics. Prebiotics are ‘non-digestible compounds that through metabolisation by microorganisms in the gut, modulate the composition and/or activity of the gut microbiota, thereby conferring a beneficial physiological effect on host’. We have additionally shown that ITFs are able to lower hepatic steatosis in n-3 PUFA-depleted wild-type (WT) mice, by modulating gene expression in the liver.

The microbiota (e.g. the enteric arterial tree) plays key roles in the metabolic diseases progression. We have evaluated for the first time the influence of ITFs in a model in which endothelial dysfunction appears independently of obesity and inflammation, both being affected by ITFs. Our model allows to point out molecular mechanisms by which changes in gut microbiota might remedy the enteric vascular dysfunction.
RESULTS
Endothelial dysfunction is improved by ITF treatment through the activation of the NO synthase/NO pathway
As expected, mesenteric arteries isolated from n-3 PUFA-depleted Apoe\(^{-/-}\) mice (KO DEF) developed a significant endothelial dysfunction, attested by the reduced vasodilation to cumulative doses of Ach (Figure 1A). Fifteen days of ITF supplementation significantly improved the relaxation of mesenteric arteries isolated from n-3 PUFA-depleted Apoe\(^{-/-}\) mice supplemented with ITFs (KO DEF ITF) as compared with WT mice, treated or not (Figure 1A). The non-selective NO synthase (NOS) inhibitor (L-NAME) completely blunted the relaxation in mesenteric resistance arteries independently of diet or genetic background, suggesting an implication of the NOS/NO pathway (Figure 1B). In line with endothelial dysfunction, KO DEF mice displayed a 40% decrease in haem-nitrosylated haemoglobin.
(Hb-NO) levels, measured by electron paramagnetic resonance, as compared with WT DEF mice. Interestingly, ITF treatment restored Hb-NO to similar levels as measured in WT mice (figure 1C). We investigated the relaxation profile of carotid arteries, another type of vessel, conductance versus resistance arteries, and at distance from the gut. The beneficial effects of ITFs on mesenteric arteries relaxation were also observed in carotid arteries isolated from KO DEF ITF mice (figure 1D). We used western blotting to assess total endothelial NOS (eNOS) as well as its activating serine 1177 phosphorylated form (p-eNOSser1177) along with its allosteric regulator, caveolin-1 (figure 1E). eNOS phosphorylation was twofold higher in mesenteric arteries from KO DEF ITF mice compared with KO DEF mice, while total eNOS protein was not significantly affected by genotype and/or diet. This resulted in a significantly increased p-eNOSser1177/eNOS ratio in mesenteric arteries isolated from KO DEF ITF mice, compared with samples from KO DEF ITF. In accordance with previous observations,26 we observed a slight increase in caveolin-1 abundance in KO DEF versus WT DEF (figure 1F).

Figure 2 Resting parameters and vascular reactivity of mesenteric arteries. (A) Resting tone (N=7–11). (B) Normalised vessel diameter (N=7–11). (C) Maximal contraction in response of KCl-enriched solution (50 mM) (N=7–11). (D) Intima-media thickness of first order mesenteric arteries (N=6–8) and (E) representative pictures (scale bar=100 μm). Data are expressed as mean±SEM and analysed by one-way analysis of variance followed by Tukey’s post-tests: * versus WT DEF, $ versus WT DEF ITF, # versus KO DEF.

ITF treatment impacts resting parameters and vascular reactivity in mesenteric arteries

Resting tone was significantly higher in mesenteric arteries isolated from KO DEF ITF mice, compared with untreated mice (figure 2A). This effect was associated with a significantly larger mean arterial diameter, as compared with WT DEF mice (figure 2B). Mesenteric arteries from KO DEF ITF mice contracted significantly more in response to KCl-enriched solution (50 mM) compared with all other groups (figure 2C). Intima-media thickness in mesenteric arteries from KO DEF mice was significantly reduced in comparison with either treated or untreated WT DEF mice (figure 2D,E). Interestingly, media remodelling was completely reversed by 15 days of ITF supplementation.

Microarray analysis highlights several pathways affected by ITF treatment

To identify the mechanisms underlying the improvement in endothelial function by ITF treatment, we analysed caecal gene expression profiles by microarray (figure 3). Further comparison focused on KO genotypes in which most effects...
were observed. ITF treatment led to an increased expression in (1) various antimicrobial peptides (e.g. Defa, Reg3β, SAA1, SAA3), (2) genes involved in bile acid (BA) metabolism (Slc10a2), (3) aminopeptidases (Anpep, Enpep) and (4) (pro)hormones, neurotensin (Nts) and proglucagon (Gcg). Quantitative PCR analyses confirmed these microarray data (see online supplementary figure S1).

**ITF treatment profoundly modifies the gut microbiota composition in WT and KO mice**

Shannon and Simpson Indexes (figure 4A), representing richness and evenness, were significantly decreased in KO DEF ITF mice compared with KO DEF mice just as well as Evenness Indexes (Simpson Evenness and Heip Indexes, figure 4B). However, the richness (measured using Chao1 and Observed Species Indexes, figure 4C) was not significantly modified in any groups. The β-diversity was also profoundly changed in ITF-treated WT and KO mice, as observed in the principal coordinates analysis (PCoA) of the Morisita-Horn Index (figure 4D) and the weighted UniFrac Index (figure 4E) at the OTU level. The three first principal coordinates respectively explained 56% and 66% of the variation observed between all the groups. In the two PCoA, we observed clustering for ITF-treated versus untreated mice, independently of genotype. At the phyla level (figure 4F), several shifts clearly operated following ITF supplementation in the two genotypes such as a decreased abundance of the Firmicutes phylum and an increased abundance of the Bacteroidetes, Actinobacteria and Proteobacteria phyla. Intriguingly, KO DEF mice presented a lower relative abundance of the Verrucomicrobia phylum compared with WT DEF mice and ITFs were able to restore its abundance (figure 4F). Parametrical analysis at lower taxonomical levels revealed additional changes. ITF had growth-fostering effects on the Erysipelotrichaceae family and *Bifidobacterium* genus in both genotypes. In line with the observations at the phylum level, abundance of *Akkermansia* genus was drastically decreased.
in KO DEF mice while the ITF treatment restored its abundance to a similar level as observed in WT mice (figure 4G). Concomitantly, ITFs also led to a decreased relative abundance of Desulfovibrionales and Clostridiales orders and of the Ruminococcaceae and Lachnospiraceae families (only in the KO genotype for the last family) (figure 4H). Discriminant analyses using LEfSe confirmed these results (figure 5). Enrichment in Actinobacteria (Bifidobacteriales and Coriobacteriales orders), Enterobacteriaceae and Erysipelotrichaceae characterised ITF-treated mice whereas enrichment in Deltaproteobacteria, Ruminococcaceae and Clostridiales was observed in untreated mice (figure 5 and see online supplementary figure S2).
appears from visual comparison of cladograms that ITFs have similar but not identical effects in both genotypes, with a few changes occurring only in KO DEF groups (such as enrichment in Bacteroidetes and Akkermansia upon ITFs). Among the 93 OTUs significantly modified by the treatments at the q-level, OTU 19, identified as *Escherichia coli*, and OTU 6, identified as *Shigella boydii*, were increased by at least 600-fold, in ITF-treated groups (see online supplementary table S1). Moreover, OTU 1, identified as *Akkermansia muciniphila*, was increased by fourfold in KO DEF ITF versus KO DEF mice, reaching 16% of the gut microbiota in KO DEF ITF mice. We also observed that six OTUs, all belonging to the Lachnospiraceae family, were drastically decreased by ITFs in both genotypes (between 127-fold and 2198-fold decrease, mostly observed in KO DEF ITF). OTU 141, identified as unclassified Ruminococcaceae, also decreased by 217-fold in KO DEF ITF as compared with KO DEF mice (see online supplementary table S1).

**ITF treatment quantitatively and qualitatively modifies plasma and caecal BA profiles**

We measured the expression of genes involved in the biosynthesis and enterohepatic cycle of BAs focusing on KO genotype,
which develop the endothelial dysfunction. ITF supplementation significantly upregulated hepatic mRNA levels of Cyp7a1, the rate-limiting enzyme of the classical BA synthesis pathway (figure 6A). Although Cyp7a1, which is mostly involved in the alternative pathway, was not affected by ITF treatment, the expression of Cyp7b1 was decreased by ITF treatment. Cyp8b1 was not modified by the ITF supplementation (figure 6A). ITF treatment significantly enhanced markers of BAs reuptake in the ileum (Slc10a2, Fabp6, Slc51a/b) (figure 6B). ITF treatment also increased the BA concentration, which was mainly due to the rise in free BAs, rather than the tauro-conjugated BAs (figure 6C–F). More precisely, the primary BAs cholic acid (CA) and chenodeoxycholic acid (CDCA) increased strongly in the portal and systemic blood as well as in the caecal content. Muricholic acid (MCA) and ursodeoxycholic acid (UDCA) were also strongly increased in blood and in caecal content. In contrast, the concentrations of the secondary BA deoxycholic acid (DCA) and its tauro-conjugated form were strongly reduced following ITF supplementation. Another secondary BA, lithocholic acid (LCA), was also significantly decreased in the caecal content by the ITF treatment (figure 6H). Caecal DCA and LCA positively correlated with abundance in unclassified Ruminococcaceae and with abundance in Lachnospiraceae and unclassified Lachnospiraceae (figure 7 and see online supplementary figure S3 and table S2). A PICRUSt analysis predicted no significant difference in primary and secondary BA biosynthesis pathways (see online supplementary table S3). These results must be taken into account with caution because of the moderate accuracy of the prediction, evidenced by a mean NSTI value of 0.10 ±0.006.27 Since Cyp7a1 also regulates cholesterol metabolism and its enteric elimination, we determined blood lipid profiles in KO DEF and KO DEF ITF mice. ITF treatment did not modify the plasma lipids profile (see online supplementary table S4).

**ITF treatment increases glucagon-like peptide 1 production**

ITF treatment in KO DEF ITF mice provoked a threefold increase in active portal glucagon-like peptide 1 (GLP-1) concentrations, as compared with KO DEF mice (figure 8A). Increased expression of Gcg and of an enzyme involved in GLP-1 maturation (namely prohormone convertase 1/3, PC1/3) were observed in KO DEF ITF mice (figure 8B). Differentiation factors NeuroD1 and neurogenin 3 (Ngn3) were not modified by ITF treatment, suggesting they are not involved in higher differentiation of enteroendocrine cells producing GLP-1. However, a large number of GLP-1-positive cells was observed in the proximal colon, thereby suggesting that overall pool of L cells is increased whereas the differentiation is not affected (figure 8C,D).28 Accordingly, correlation analysis revealed that Gcg mRNA positively correlates with the abundance of Bifidobacteriaceae and Verrucomicrobiaceae families, both enhanced by ITFs, and negatively correlates with the abundance of Ruminococcaceae and Lachnospiraceae families (figure 8E).

**DISCUSSION**

Metabolic diseases such as non-alcoholic fatty liver disease are associated with macro- and microcirculation and microcirculation damage, initiating an impairment of endothelium-dependent relaxation.19 29 Here, we demonstrate that supplementation in ITF for 15 days corrects the endothelial dysfunction – an early key biomarker of CVDs – present in n-3 PUFA-depleted Apoe−/− mice.

Blood vessels are assumed to respond to varying conditions and functional demands through continuous adaptive structural changes. Accordingly following ITF treatment, we observed an increase in mesenteric diameter and wall thickness associated with increasing contractile reactivity, all needed to ensure stable vascular adaptation. Interestingly, the favourable outward remodelling, observed locally, was also characterised by improved NO-dependent endothelium relaxation. In most cases, endothelial dysfunction is related to a reduced NO availability in mice.30 Inhibiting the NOS/NO pathway with L-NAME totally masked the vasodilation in mice, abolishing the positive effect of ITFs. The increased ratio of p-eNOSSer1177 to total eNOS suggests that ITFs activate the NOS/NO pathway in Apoe−/− mice.

Of more relevance for human CVD, effects of ITFs were not restricted to the enteric vascular tree, such effects were also observed at a distance from the mesenteric bed as indicated by the recovery of the circulating level of Hb-NO in peripheral blood and the improved relaxation in carotid arteries. Whether the molecular mechanisms underlying the improved NO-dependent relaxation in the carotid artery fully reflect those involved in the mesenteric tree remains elusive at this stage.

Weight loss can improve the impairment of endothelium-dependent relaxation;41 however, this hypothesis can be ruled out in our study as no change in body weight was observed in ITF-treated versus untreated mice (see online supplementary table S5).

The Erysipelotrichaceae family, belonging to the Firmicutes phylum, was expanded by ITFs. It has been previously reported that dietary intervention such as prebiotics or berberine in high-fat-fed mice concomitantly led to an expanded abundance of Allobaculum sp – an important member of the Erysipelotrichaceae family – and to an improvement in metabolic parameters, suggesting a potential beneficial contribution of Allobaculum sp to host phenotype.32 33 In agreement with these observations, ITFs increased OTU 4, closely related to Allobaculum sp (90.4%), by tenfold in ITF-treated Apoe−/− mice. Furthermore, abundance in Erysipelotrichaceae was strongly and positively correlated with portal CDCA, UDCA and MCA but not to their conjugates.

Abundance of Akkermansia, a bacterium capable of reducing fat mass development, insulin resistance and dyslipidaemia in obese mice,11 12 was quadrupled by ITFs in Apoe−/− mice, reaching the same level as that observed in WT mice. In addition, it has been reported that Akkermansia positively correlates with higher levels of circulating primary BAs;34 it is in accordance with the positive correlation observed between circulating CA and this bacterium. Based on the results of multiple correlation analyses, we propose that the marked decreases in the Lachnospiraceae and Ruminococcaceae families caused by ITFs contribute to the drop in DCA and LCA concentration, since they are among the dominant families able to produce secondary BAs through 7α-dehydroxylation. These observations are consistent with previous studies showing, in humans and mice with liver diseases, an association between abundance of Ruminococcaceae and Lachnospiraceae families and secondary BA concentrations.35 36 The Desulfovibrionales order, known to be increased by high-fat diet and associated with inflammation and/or altered gut barrier in mouse models,13 37 38 was also decreased by at least twofold in ITF-supplemented mice and strongly correlated with DCA concentration in Apoe−/− mice. We can therefore propose that changing the microbial composition using ITFs impacts largely the production of secondary BAs and could contribute to the improvement of the host’s health.

Changes in BA profiles by ITF treatment also result from the modulation of BA metabolism, including hepatic synthesis (in...
Figure 6 Bile acid (BA) metabolism affected by inulin-type fructans (ITF) supplementation in KO genotype. (A) Genes involved in BA biosynthesis and its regulation (N=11–12). (B) Genes involved in the enterohepatic cycle (N=8–12). (C) Ratio of free and conjugated to total BAs in systemic blood (N=6). (D) Systemic BA profile (N=6). (E) Ratio of free and conjugated to total BAs in portal blood (N=5–6). (F) Portal BA profile (N=5–6). (G) Ratio of free and conjugated to total BAs in caecal content (N=6). (H) Caecal BA profile (N=6). Data are expressed as mean±SEM and analysed by unpaired t-test: # versus KO DEF.
Figure 7  Heatmap representation of the Spearman’s r correlation coefficient between caecal bile acid profile and bacterial taxa. Only the bacteria, for which at least one significant correlation to bile acid levels was found, are displayed (c, class; o, order; f, family; g, genus; s, species).
* Adjusted p value <0.05.

Coriobacteriales_o
Coriobacteriidae_s
Coriobacterinaceae_s
Coriobacteriaceae_f
unclassified_Coriobacteriaceae
Parasutterellaceae_g
Sutterellaceae_f
Burkholderiales_o
Betaproteobacteria_c
Actinobacteria_c
Actinobacteria_p
Porphyromonadaceae_f
Parabacteroides_g
unclassified_Erysipelotrichaceae
Bacteroidia_c
Bacteroidetes_p
Bacteroidales_o
Anaerotruncus_g
Enterobacteriaceae_f
Enterobacteriales_o
Gammaproteobacteria_c
unclassified_Enterobacteriaceae
Enterococcus_g
Enterococcaceae_f
Butyricimonas_g
Escherichia/Shigella_g
Bacteroides_g
Bacteroidaceae_f
unclassified_Selenomonadales
Selenomonadaceae_o
Negativicutes_c
Pseudoflavonifractor_g
Oscillibacter_g
Clostridium_IV_g
Butyricoccus_g
Mucispirillum_g
Deferribacteraceae_f
Deferribacterales_o
Deferribacteres_c
Deferribacteres_p
unclassified_Porphyromonadaceae
Flavonifractor_g
Barnesiella_g
unclassified_Ruminococcaceae
Lachnospiraceae_f
unclassified_Lachnospiraceae
Clostridiales_o
Clostridium_c
unclassified_Proteobacteria
unclassified_Desulfovibrionales
Desulfovibrionales_o
Deltaproteobacteria_c
unclassified_Deltaproteobacteria
unclassified_Bacteria
unclassified_Clostridia
Clostridium_XIVb_g
unclassified_Clostridiales
Ruminococcaceae_f
Firmicutes_p

Spearman r

-0.5  0.5

Primary  Secondary  Primary  Secondary
FREE BAs  TAURO-CONJUGATED BAs
Prebiotic treatment increases glucagon-like peptide 1 (GLP-1) production. (A) Active GLP-1 concentration (N=9–10). (B) Proglucagon (Gcg), NeuroD1, neurogenin 3 (Ngn3) and prohormone convertase 1/3 (PC1/3) expression in proximal colon (N=7–8). (C) L cell density in proximal colon (N=6–8). (D) Representative immunofluorescence staining for L cell density. CK8+18 (green), GLP-1 (red) and DNA (blue) in proximal colon (scale bar=200 μm). Data are expressed as mean±SEM and analysed by unpaired t-test: # versus KO n-3 PUFA-depleted (DEF). (E) Heatmap representation of the Spearman’s r correlation coefficient between caecal expression of gene highlighted by the microarray analysis and confirmed by qPCR, and bacterial taxa. Only the bacteria for which at least one significant correlation to genes expression was found, are displayed (c, class; o, order; f, family; g, genus; s, species). *Adjusted p value <0.05.

favour of Cyp7a1) and intestinal reuptake. In the liver, BA-activated Farnesoid X receptor (FXR) induces the expression of small heterodimer partner (Shp) which can inhibit Cyp7a1 expression; both are negatively correlated in our study (Spearman’s r = -0.62; p = 0.0014). Although FXR mRNA expression was not affected by ITFs, α and β MCAs (free or tauro-conjugated) induced by ITFs, have FXR antagonistic properties9 40 and may contribute to the Cyp7a1 upregulation. In addition, ITFs enhance BA reabsorption, which is negatively associated with changes in Ruminococcaceae and Lachnospiraceae families and positively associated with the Bifidobacteriaceae and Erysipelotrichiaceae families and the Akkermansia genus. Enterobacteriaceae were largely expanded by the ITF supplementation and were dominated by E. coli/Shigella (identified as OTUs 19 and 6, respectively) in our study. Interestingly, bacteria like E. coli, can produce NO either enzymatically from L-arginine via bacterial NOS or non-enzymatically through nitrite reduction.41 42 Another bacterial family increased by ITFs that may contribute to NO generation is the Bifidobacteriaceae family. Indeed, by decreasing the pH, bifidobacteria may generate more NO than any other species through the acidic non-enzymatic reduction of nitrite.43

The promotion of GLP-1 release by ITFs appears to be another potential link between events occurring in the bacterial ecosystem and improvement of endothelial function, since Bifidobacterium as well as Akkermansia are positively correlated with mRNA expression of Gcg and Nts, being coexpressed and co-released with GLP-1.44 Moreover, GLP-1 infusion or GLP-1 receptor agonists can correct endothelial dysfunction, in humans as well as rats, improving serine phosphorylation of eNOS in vitro (data not shown). In addition, TGR5 is highly expressed in enteroendocrine L cells in the small intestine and stimulates GLP-1 secretion, thus indirectly improving the endothelial function.49 50 Plasmatic LDLc and HDLc levels were similar in all groups of mice. Although lipid profiles were measured in mice that were not rigorously fasted, and therefore might be not completely accurate, it is very unlikely that different lipoprotein plasma levels contributed to the beneficial effects of ITFs.

The improvement of enteric vascular dysfunction by ITFs could relate to events occurring at microbial level (e.g. increase in NO-producing bacteria) and/or at host level (e.g. changes in endothelial functions, and can be considered as a rationale to evaluate such an effect in a human intervention study. For sure, the dose at which ITF would be tested is below the one given to animals (0.25 g/day). In human intervention studies, doses ranging from 12g/day to 16 g/day are often given when testing for metabolic effects of ITF.51–54 In addition, there are certainly differences between humans and mice concerning the gut microbiota composition, but it is rather interesting to point out that similar bacterial changes occur in both humans and mice upon prebiotic intervention (e.g. in favour of the Bifidobacterium genus).55 56 While effects on gut function (e.g. increase in GLP-1 production by prebiotics) have been largely described in rodent models, several papers also reported the influence of prebiotics in humans.3 1–5

In conclusion, our findings pave the way for innovative therapeutic approaches in prevention of human vascular dysfunction, for which no treatment has been successfully proposed so far.

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