Common variants associated with *OSMR* expression contribute to carotid plaque vulnerability, but not to cardiovascular disease in humans

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Abstract

Background and aims

Oncostatin M (OSM) signaling is implicated in atherosclerosis, however the mechanism remains unclear. We investigated the impact of common genetic variants in *OSM* and its receptors, *OSMR* and *LIFR,* on overall plaque vulnerability, plaque phenotype, intraplaque *OSMR* and *LIFR* expression, coronary artery calcification burden and cardiovascular disease susceptibility.

Methods and results

We queried Genotype-Tissue Expression data and found rs13168867 (C allele) and rs10491509 (A allele) to be associated with decreased *OSMR* and increased *LIFR* expression in arterial tissue respectively. No variant was significantly associated with *OSM* expression.

We associated these two variants with plaque characteristics from 1,443 genotyped carotid endarterectomy patients in the Athero-Express Biobank Study. After correction for multiple testing, rs13168867 was significantly associated with an increased overall plaque vulnerability (β=0.118 ± s.e.=0.040, p=3.00x10^{-3}, C allele). Looking at individual plaque characteristics, rs13168867 showed strongest associations with intraplaque fat (β=0.248 ± s.e.=0.088, p=4.66 x 10^{-3}, C allele) and collagen content (β=-0.259 ± s.e.=0.095, p=6.22 x 10^{-3}, C allele), but these associations were not significant after correction for multiple testing. rs13168867 was not associated with intraplaque *OSMR* expression. Neither was intraplaque *OSMR* expression associated with plaque vulnerability and no known *OSMR* eQTLs were associated with coronary artery calcification burden, or cardiovascular disease susceptibility. No associations were found for rs10491509 in the *LIFR* locus.

Conclusions

Our study suggests that genetically decreased arterial *OSMR* expression contributes to increased carotid plaque vulnerability. However, given the lack of association with cardiovascular disease risk, the OSM signaling pathway is unlikely to be causal to lifetime cardiovascular disease susceptibility.

1. Introduction

The prevalence of cardiovascular disease (CVD) is high, poses a significant global burden and is expected to rise(1). Arterial inflammation, leading to asymmetric focal arterial thickening and atherosclerotic plaque formation and progression, is the primary mechanism underlying CVD(2). Inflammatory cytokines contribute to arterial inflammation and subsequent atherosclerotic plaque formation(3). One cytokine, for which there is mounting evidence suggesting a role in atherosclerosis development is OSM(4,5). It has been shown that OSM is present in both murine and human atherosclerotic plaques(6). Moreover, murine studies showed that OSM receptor (OSMR)$^{-/-}$ApoE$^{-/-}$ mice have reduced plaque size and improved plaque stability compared to their *OSMR*-expressing littermates(7), indicating that OSM drives atherosclerosis development. These observations are in line with our previous work, in which we showed that simultaneous signaling of OSM through OSMR and leukemia inhibitory factor receptor (LIFR), induces activation in human endothelial cells, suggestive of a role in atherosclerosis development(8). In contrast, chronic OSM administration to APOE*3Leiden.CETP mice reduces the atherosclerotic lesion size and severity, and high circulating OSM levels correlate with increased post-incident coronary heart disease survival probability in humans(9).

Although all these studies implicate that OSM is involved in atherosclerosis, little is known about the effects of OSM on plaque composition in humans. Grouped in the interleukin 6 subfamily of cytokines, OSM is released by activated immune cells(10–12), and exerts pleiotropic effects on cell proliferation, inflammation, hematopoiesis, tissue remodeling, and development(13). Its signals are transduced through binding to either OSMR or LIFR, which form a heterodimer with glycoprotein 130(8,14), that in turn activates multiple pathways(14). It is suggested that the ratio of the two receptor types expressed on the cell membrane is a potential regulatory mechanism for the multiple, and sometimes opposing, effects that are exerted by OSM(15).

Thus, given its pleiotropic function, it is difficult to predict how OSM contributes to atherosclerotic plaque formation. Cell and murine studies have shown that OSM promotes angiogenesis(4), endothelial activation(8), vessel permeability(16), and osteoblastic differentiation(17). Therefore, increased OSM levels hypothetically results in a higher intraplaque microvessel density, intraplaque hemorrhages and plaque calcification, thereby contributing to plaque destabilization(18,19). In other cell and murine studies, OSM promotes fibroblast proliferation(20), collagen formation(20), smooth muscle cell proliferation(6), and M2 macrophage polarization(21). These processes hypothetically lead to enhanced fibrosis, and attenuated inflammation, thereby contributing to plaque stabilization(22).

Large-scale studies have shown that *cis*-acting genetic variants associated to gene expression (expression quantitative trait loci (eQTLs)(23)) are key to disease susceptibility(24). This means that gene expression differs between individuals carrying different genotypes (for example AA, Aa, aa) for a given eQTL in a given tissue which ultimately results in differential disease susceptibility. Thus, on the premise that alleles are randomly distributed at conception and are invariant throughout a lifetime, meaning that genetics is not influenced by disease or risk factors, eQTLs can be used as proxies of gene expression to examine the effect on plaque morphology(25). We hypothesized that if *OSM*, *OSMR*, or *LIFR* expression has an effect on plaque morphology, these phenotypic differences will be observed among genotype groups of the eQTL. We aimed to investigate the double-edged sword of OSM signaling on the composition of human atherosclerotic plaques using known eQTLs of *OSM*, *OSMR*, and *LIFR*.

2. Materials and methods

2.1 Sample collection

The Athero-Express Biobank Study (https://www.atheroexpress.nl) is an ongoing prospective study, containing biomaterial of patients elected for endarterectomy at two Dutch tertiary referral centers. Details of the study design were described before(26). Briefly, blood subfractions are obtained before and arterial plaque material during endarterectomy. Each plaque is dissected into segments of 0.5cm. The culprit lesion is reserved for histological assessment (see below), while surrounding segments are immediately snap frozen in liquid nitrogen and stored at -80°C for later use, e.g., in order to perform RNA-seq (see below). Only carotid endarterectomy (CEA) patients were included in the present study. All research was conducted according to the principles of the Declaration of Helsinki and its later amendments, all patients provided informed consent and the study was approved by the medical ethics committees.

2.2 Athero-Express genotyping, quality control, and imputation

Details of genotyping were previously described(26). Briefly, DNA was extracted from EDTA blood or (when no blood was available) plaque samples of 1,858 consecutive patients from the Athero-Express Biobank Study and genotyped in 2 batches. For the Athero-Express Genomics Study 1 (AEGS1), 836 patients, included between 2002 and 2007, were genotyped using the Affymetrix Genome-Wide Human SNP Array 5.0 (SNP5) chip (Affymetrix Inc., Santa Clara, CA, USA). For the Athero-Express Genomics Study 2 (AEGS2), 1,022 patients, included between 2002 and 2013 and not overlapping AEGS1, were genotyped using the Affymetrix Axiom® GW CEU 1 Array (AxM).

Both studies were carried out according to OECD standards. After genotype calling, we adhered to community standard quality control and assurance (QA/QA) procedures of the genotype data from AEGS1 and AEGS2. Samples with low average genotype calling and sex discrepancies (compared to the clinical data available) were excluded. The data was further filtered on 1) individual (sample) call rate >97%, 2) SNP call rate >97%, 3) minor allele frequencies (MAF) >3%, 4) average heterozygosity rate ± 3.0 s.d., 5) relatedness (pi-hat >0.20), 6) Hardy–Weinberg Equilibrium (HWE $p < 1.0 \times 10^{-6}$), and 7) population stratification (based on HapMap 2, release 22, b36) by excluding samples deviating more than 6 standard deviations from the average in 5 iterations during principal component analysis (PCA) and by visual inspection as previously described(26). After QA/QA, 657 samples and 403,789 SNPs in AEGS1, and 869 samples and 535,983 SNPs in AEGS2 remained. To correct for genetic ancestry and population stratification we performed PCA in each cleaned dataset to obtain principal components for downstream analyses as descibred before(26).

Before phasing using SHAPEIT2(27), data was lifted to genome build b37 using the liftOver tool from UCSC (https://genome.ucsc.edu/cgi-bin/hgLiftOver). Finally, data was imputed with 1000G phase 3(28) and GoNL 5(29) as a reference. Note that we only selected the CEA patients in these datasets, leaving 1,443 samples for our further analyses.

2.3 Variant selection

We queried data from the Genotype-Tissue Expression (GTEx) Portal (https://gtexportal.org)(23) for *cis*-acting variants (defined as variants within 1Mb of a given gene) that alter *OSM* expression in blood, and *OSMR* or *LIFR* expression in non-diseased arterial tissue. We selected common variants with a MAF >3%, which yielded 2 variants in total. We harmonized the effect alleles and effect sizes from these eQTLs to match the allele orientation in the Athero-Express Biobank Study data.

2.4 Plaque phenotyping

The (immuno)histochemical analysis of plaques have been described previously(26,30,31). Briefly, per plaque, the culprit lesion was identified directly after dissection, fixed in 4% formaldehyde, embedded in paraffin and cut in 5µm sections on a microtome for (immuno)histochemical analysis by pathology experts. Calcification (hematoxylin & eosin, H&E) and collagen content (picrosirius red) were semi-quantitatively scored and defined as no/minor or moderate/heavy. Atheroma size (H&E and picrosirius red) was defined as <10% or ≥10% fat content. Macrophages (CD68) and smooth muscle cells (ACTA2) were quantitatively scored and classified as percentage of plaque area. Intraplaque hemorrhage (H&E) was defined as absent or present, and vessel density was classified as the number of intraplaque vessels (CD34) per 3-4 hotspots.

2.5 Plaque vulnerability

Assessment of overall plaque vulnerability was performed as previously described by Verhoeven *et al*(25). Briefly, macrophages and smooth muscle cells were semi-quantitatively defined as no/minor or moderate/heavy. Each plaque characteristic that defines a stable plaque (i.e., no/minor macrophages, moderate/heavy collagen, moderate/heavy smooth muscle cells and <10% fat) was given a score of 0, while each plaque characteristic that defines a vulnerable plaque (i.e., moderate/heavy macrophages, no/minor collagen, no/minor smooth muscle cells and ≥10% fat) was given a score of 1. The score of each plaque characteristic was summed resulting in a final plaque score ranging from 0 (most stable plaque) to 4 (most vulnerable plaque). Intraobserver and interobserver variability were examined previously and showed good concordance (κ=0.6-0.9)(32).

2.6 Plaque expression

To be able to assess the global expression profile, plaque segments were thawed, cut up, and further homogenized using ceramic beads and tissue homogenizer (Precellys, Bertin instruments, Montigny-le-Bretonneux, France), in the presence of TriPure (Sigma Aldrich), and RNA was isolated according to TriPure manufacturer's protocol. From here, RNA in the aqueous phase was precipitated using isopropanol, and washed with 75% ethanol, and subsequently stored in 75% ethanol for later use or used immediately after an additional washing step with 75% ethanol.

Library preparation

From here, library preparation was performed, adapting the CEL-Seq2 protocol for library preparation(33,34), as described before(35). After removing ethanol, and air-drying the pellet, primer mix containing 5ng primer per reaction was added, initiating primer annealing at 65°C for 5min. Subsequent RT reaction was performed; first strand reaction for 1h at 42°C, heat inactivated for 10m at 70°C, second strand reaction for 2h at 16°C, and then put on ice until proceeding to sample pooling. The primer used for this initial reverse-transcription (RT) reaction was designed as follows: an anchored polyT, a unique 6bp barcode, a unique molecular identifier (UMI) of 6bp, the 5' Illumina adapter and a T7 promoter, as described(35). Each sample now contained its own unique barcode, due to the primer used in the RNA amplification making it possible to pool together complementary DNA (cDNA) samples at 7 samples per pool. cDNA was cleaned using AMPure XP beads (Beckman Coulter), washed with 80% ethanol, and resuspended in water before proceeding to the *in vitro* transcription (IVT) reaction (AM1334; Thermo-Fisher) incubated at 37°C for 13 hours. Next, primers were removed by treating with Exo-SAP (Affymetrix, Thermo-Fisher) and amplified RNA (aRNA) was fragmented, and then cleaned with RNAClean XP (Beckman-Coulter), washed with 70% ethanol, air-dried, and resuspended in water. After removing the beads using a magnetic stand, RNA yield and quality in the suspension were checked by Bioanalyzer (Agilent).

221 cDNA library construction was then initiated by performing an RT reaction using SuperScript
222 II reverse transcriptase (Invitrogen/Thermo-Fisher) according to the manufacturer's
223 protocol, adding randomhexRT primer as random primer. Next, PCR amplification was done
224 with Phusion High-Fidelity PCR Master Mix with HF buffer (NEB, MA, USA) and a unique
225 indexed RNA PCR primer (Illumina) per reaction, for a total of 11-15 cycles, depending on
226 aRNA concentration, with 30 seconds elongation time. PCR products were cleaned twice with
227 AMPure XP beads (Beckman Coulter). Library cDNA yield and quality were checked by Qubit
228 fluorometric quantification (Thermo-Fisher) and Bioanalyzer (Agilent), respectively. Libraries
229 were sequenced on the Illumina Nextseq500 platform; paired end, 2 x 75bp.

230 *Mapping*
231 Upon sequencing, retrieved fastq files were de-barcoded, split into forward and reverse
232 reads. Subsequently, these were mapped making use of Burrows-Wheel aligner (BWA(36))
233 version 0.7.17-r1188, calling 'bwa aln' with settings -B 6 -q 0 -n 0.00 -k 2 -l 200 -t 6 for R1
234 and -B 0 -q 0 -n 0.04 -k 2 -l 200 -t 6 for R2, 'bwa sampe' with settings -n 100 -N 100, and
235 a cDNA reference (assembly hg19, Ensembl release 84). Read counts and UMI counts were
236 derived from SAM files using custom perl code, and then gathered into count matrices.
237 Genes were annotated with Ensembl ID's, and basic quality control was performed,
238 encompassing filtering out samples with low gene numbers (<10,000 genes), and read
239 numbers (<18,000 reads). These steps resulted in 641 samples with up to 60,674 genes
240 (Ensembl ID's), and median of 178,626 reads per sample.

241 *Data analysis*
242 Stability scores, and genotypes for rs10491509 and rs13168867, were added to metadata,
243 upon which this was combined with counts and annotation in a SummarizedExperiment
244 object(37). Counts were normalized and transformed making use of the variance
245 stabilization transformation function (vst()) in DESeq2(38). This results in transformed data
246 on a $\log_2$-scale, normalized for library size. Differential expression analysis between stability
247 scores or genotypes was performed using DESeq2. To test for statistical difference when
248 comparing intraplaque *OSMR* expression of the more vulnerable plaques to the least
249 vulnerable plaque, a multinomial logistic regression analysis was performed.

250 **2.7 Genetic analyses**
251 Quantitatively scored characteristics (macrophages, smooth muscle cells, and the vessel
252 density) were Box-Cox transformed(39) to obtain a normal distribution. For genetic
253 analyses we used GWASToolKit (https://swvanderlaan.github.io/GWASToolKit/) which is a
254 wrap-around collection of scripts for SNPTEST(40). Continuous and categorical variables
255 were tested using linear and logistic regression models, respectively. Models for genetic
256 analyses were corrected for age, sex, genotyping chip, and genetic ancestry using principal
257 components 1 through 4.

258 **2.8 Multiple testing and power**
259 Correction for multiple testing resulted in a corrected p-value of p=0.05/((7 plaque
260 phenotypes + plaque vulnerability) x 2 common variants)=3.13×10^{-3}. The power of the
261 study was estimated at ±75% based on a sample size of 1,443, a minor allele frequency
262 (MAF) of 0.409 and a relative risk of 1.28
263 (http://csg.sph.umich.edu/abecasis/cats/gas_power_calculator/).

264 **2.9 Data and scripts**
265 Data is available upon request. Scripts are posted at GitHub
266 https://github.com/swvanderlaan/2019_vankeulen_d_osmr.

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3. Results

3.1 Common variants altering *OSM*, *OSMR* and *LIFR* expression

We included and genotyped 1,443 carotid endarterectomy patients in this study. We combined these groups (**Table 1**) for overall plaque vulnerability and phenotype analyses, as we previously showed that the baseline characteristics between the two genotyping groups (AEGS1 and AEGS2) are comparable(26).

Table 1: Baseline characteristics of genotyped CEA patients from the Athero-Express Biobank Study. Cerebrovascular disease history is defined by ischemic stroke prior to surgery. Coronary artery disease history includes diagnosed coronary artery disease, myocardial infarction, percutaneous coronary intervention, and coronary artery bypass grafting. Peripheral disease history includes diagnosed peripheral arterial occlusive disease, femoral artery interventions, and ankle-brachial index <70. Type 2 diabetes mellitus includes all individuals with diagnosed type 2 diabetes mellitus and those on appropriate medication. Hypertension includes all individuals with self-reported hypertension. Current smokers include all individuals smoking up to 6 months until the surgery date. BMI, kg/m^2. eGFR rate was based on the Modification of Diet in Renal Disease formula, mL/min/1.73m^2. Anti-hypertensives include all anti-hypertension medication. Anti-thrombotics include clopidogrel, dipyridamole, acenocoumarol, ascal, and other anti-platelet drugs. Missing data shows the percentage of the patients of which we lack information on the specific patient characteristic.

Patient characteristics		**Missing data (%)**
Sex, male, n (%)	976 (64.0)	5.7
Age in years, mean (SD)	68.84 (9.33)	5.7
History		
Cerebrovascular disease, n (%)	478 (33.2)	5.7
Coronary artery disease, n (%)	430 (29.9)	5.8
Peripheral artery disease, n (%)	297 (20.7)	5.8
Risk factors		
Type 2 diabetes mellitus, n (%)	332 (23.1)	5.7
Hypertension, n (%)	1017 (73.0)	8.7
Current smoker, n (%)	492 (34.9)	7.5
BMI, median [IQR]	26.0 [24.0-28.4]	11.5
eGFR, median [IQR]	72.3 [58.7-85.4]	8.1
Total cholesterol in mmol/L, median [IQR]	4.38 [3.60-5.25]	22.8
LDL in mmol/L, median [IQR]	2.40 [1.81-3.13]	27.8

HDL in mmol/L, median [IQR]	1.06 [0.87-1.30]	25.0
Triglycerides in mmol/L, median [IQR]	1.50 [1.08-2.04]	24.6
Medication		
Anti-hypertensives, n (%)	1110 (77.2)	5.8
Lipid lowering drugs, n (%)	1112 (77.4)	5.8
Anti-thrombotics, n (%)	1272 (88.6)	6.0
Symptoms		
Asymptomatics, n (%)	195 (13.6)	6.0
Ocular, n (%)	221 (15.4)	6.0
TIA, n (%)	634 (44.2)	6.0
Stroke, n (%)	384 (26.8)	6.0

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288 OSM is secreted by, among others, neutrophils(12), monocytes(11), macrophages(11) and
289 T-cells(10), and acts through binding to OSMR and LIFR(14,41,42) in the arterial wall(7,43).
290 Thus we queried data from the Genotype-Tissue Expression project (GTEx)(23) for SNPs
291 that alter *OSM* expression in whole blood and *LIFR* and *OSMR* expression in arterial tissue.
292 There were no significant eQTLs for *OSM*, but there were two eQTLs associated with altered
293 *OSMR* (rs13168867) or *LIFR* (rs10491509) expression in arterial tissue. The C allele of
294 rs13168867 is associated with decreased *OSMR* expression in the tibial artery (**Figure 1A**),
295 and the A allele of rs10491509 is associated with increased *LIFR* expression in the aortic
296 artery (**Figure 1B**). Cross-tissue meta-analysis showed that these variants have m-values
297 >0.9 in both tibial and aortic artery tissue, indicating a high posterior probability that they
298 are single *cis*-eQTLs in both tissues (**Supplemental Figure 1** and **2**).

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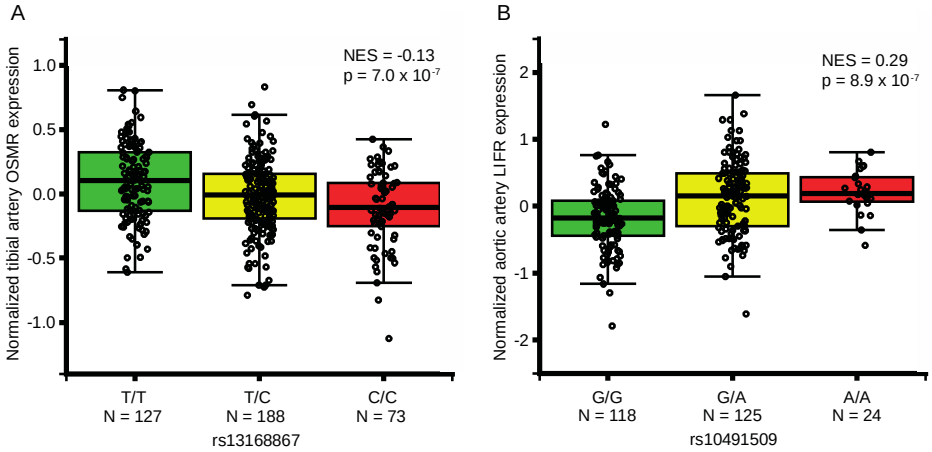
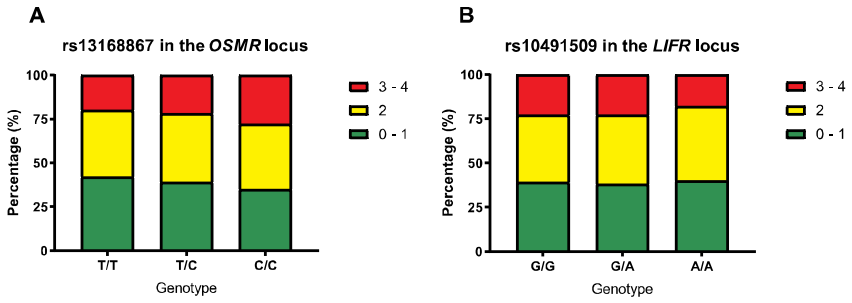


Figure 1: Association of *OSMR* and *LIFR* variants in non-diseased arterial tissues. Per variant, the normalized expression of *OSMR* **(A)** and *LIFR* **(B)** is given in non-diseased arterial tissue. Data from GTEx Portal (www.gtexportal.org). NES: Normalized effect size. In aortic arterial tissue, rs13168867 had a NES of -0.123 and in tibial arterial tissue, rs10491509 had a NES of 0.0881 (**Supplementary Figure 1** and **2**).

3.2 Genetic association with plaque vulnerability

To determine the effect of OSM signaling on the overall plaque vulnerability, we correlated the rs13168867 and rs10491509 genotypes to the overall plaque vulnerability, which was given a score ranging from 0 (least vulnerable plaque) to 4 (most vulnerable plaque). The effect allele of variant rs13168867 in the *OSMR* locus was significantly correlated with an increased overall plaque vulnerability (β=0.118 ± s.e.=0.040 (C allele), p=3.00x10^{-3}, **Figure 2**). No association was observed with rs10491509 and overall plaque vulnerability.



Gene	Variant	NES	Alleles	EAF	Info	β (s.e.)	*p*
OSMR	rs13168867	-0.13	C/T	0.393	0.999	0.118 (0.040)	**3.00 x 10^{-3}**
LIFR	rs10491509	0.29	A/G	0.351	0.989	0.001 (0.043)	0.981

Figure 2: Association of *OSMR* and *LIFR* variants with overall plaque vulnerability. The plaques were given a vulnerability score ranging from 0 (least vulnerable) to 4 (most vulnerable). The bars represent the proportion of each plaque score per genotype for rs13168867 in the *OSMR* locus **(A)** and rs10491509 in the *LIFR* locus **(B)**. NES: normalized effect size on expression (GTEx Portal, www.gtexportal.org(23)); Alleles: the effect allele and the other allele, respectively; EAF: effect allele frequency in the Athero-Express Biobank; Info: estimated imputation score in the Athero-Express Biobank; β: effect size; s.e.: standard error; p: p-value of association; Bold p: p-value of association surpasses significance threshold (p <3.13x10^{-3}).

3.3 Genetic association with plaque phenotypes

To determine the effect of OSM signaling on the individual plaque characteristics comprising the overall plaque vulnerability, we assessed the association between rs13168867 and rs10491509 and seven plaque phenotypes in the Athero-Express Biobank Study. Although not significant after correction for multiple testing, the strongest associations were observed between the effect allele of variant rs13168867 in the *OSMR* locus and intraplaque fat (β=0.248 ± s.e.=0.088 (C allele), p=4.66x10^{-3}), and collagen content (β=-0.259 ± s.e.=0.095 (C allele), p=6.22x10^{-3}, **Table 2**). No associations were observed between rs10491509 and any of the plaque phenotypes.

Table 2: *OSMR* and *LIFR* variants and their association with plaque phenotypes. For each variant, the association with plaque phenotypes is given. NES: the normalized effect size on expression; Alleles: the effect allele and the other allele, respectively; EAF: effect allele frequency in the Athero-Express Biobank; Info: estimated imputation score in the Athero-Express Biobank; β: effect size; s.e.: standard error; p: p-value of association; Adj. p: Bonferroni adjusted p-value. Calcification and collagen were classified as no/minor vs moderate/heavy, fat content as 10% vs >10% fat of plaque area, intraplaque hemorrhage was classified as absent vs present. Smooth muscle cells and macrophages were classified as Box-Cox transformed percentage of plaque area and vessel density as Box-Cox transformed number of vessels/hotspot. None of the p-values surpassed significance threshold (3.13x10^{-3}).

Gene	Variant	NES	Alleles	EAF	Info	Phenotype	β (s.e.)	*p*
OSMR	rs13168867	-0.13	C/T	0.393	0.999	Calcification	0.036 (0.077)	0.637
						Collagen	-0.259 (0.095)	6.22 x 10^{-3}
						Fat content	0.248 (0.088)	4.66 x 10^{-3}
						Intraplaque hemorrhage	-0.014 (0.080)	0.862
						Smooth muscle cells	0.001 (0.011)	0.913
						Vessel density	-1.06x10^{-4} (0.004)	0.976
						Macrophages	0.004 (0.015)	0.809
LIFR	rs10491509	0.29	A/G	0.351	0.989	Calcification	0.046 (0.082)	0.577
						Collagen	0.134 (0.104)	0.194
						Fat content	0.086 (0.094)	0.363
						Intraplaque hemorrhage	0.071 (0.086)	0.414
						Smooth muscle cells	-0.003 (0.012)	0.840

						Vessel density	0.002 (0.004)	0.577
						Macrophages	0.015 (0.016)	0.354

3.4 Known eQTLs of *OSMR* and *LIFR* expression in non-diseased arterial tissue are not associated with expression in atherosclerotic plaques

Atherosclerotic disease progression changes the artery-specific transcriptional dynamics, and may therefore abolish the effects of known *OSMR* and *LIFR* eQTLs in non-atherosclerotic arterial tissues. Thus, we tested whether these eQTLs were associated with *OSMR* and *LIFR* expression in carotid atherosclerotic plaques. Neither variant showed associations with expression of *OSM*, *OSMR*, and *LIFR* (**Supplementary Table 1**).

3.5 Intraplaque *OSMR* expression is not associated with plaque vulnerability

As rs13168867 was associated with an increased overall plaque vulnerability, we next investigated if intraplaque *OSMR* expression levels associated with overall plaque vulnerability. Differential expression analyses, comparing the reference score (0) with each increasing vulnerability score (1, 2, 3, or 4) showed no associations between *OSMR* plaque expression levels and plaque vulnerability (**Supplemental Table 2**). Neither did intraplaque *OSM* or *LIFR* expression associate with plaque severity.

3.6 Known eQTLs of *OSMR* and *LIFR* do not associate with cardiovascular diseases

The Athero-Express comprises patients with advanced stage atherosclerotic plaques. Therefore, we assessed the effect of known *OSMR* and *LIFR* eQTLs on coronary calcification (CAC) as intermediate phenotype of atherosclerotic burden, and primary cardiovascular outcomes as clinical manifestation. We queried summary statistics from GWAS on CAC (n=2,674)(44), coronary artery disease (CAD, n=336,755)(44,45), and ischemic stroke subtypes (sample sizes 242,573-522,258)(44–46). Neither eQTL associated with increased CAC burden, or cardiovascular disease susceptibility (**Supplemental Table 3**).

4. Discussion

We investigated whether common variants associated to gene expression, i.e., eQTLs, near *OSM, OSMR* and *LIFR* affect overall plaque vulnerability and phenotype. We showed that one *cis*-acting eQTL (rs13168867, C/T), of which the C allele associates with reduced *OSMR* expression in non-diseased arterial tissue, significantly associates with increased plaque vulnerability after correction for multiple testing. This suggests that a decrease in *OSMR* expression and therefore possibly a decrease in OSM signaling, increases the chance of developing a vulnerable plaque.

To gain further insight into the role of genetically decreased *OSMR* expression on developing a vulnerable plaque, we examined the effect of rs13168867 on individual plaque characteristics in more detail. The strongest associations were found for rs13168867 with increased intraplaque fat and decreased collagen content, suggesting that reduced OSM signaling results in a larger lipid core and less fibrosis - in line with a more vulnerable plaque phenotype. We previously showed that OSM enhances intercellular adhesion molecule (ICAM)-1 expression on human endothelial cells(8). Reduced *OSMR* expression, which hypothetically results in reduced OSM signaling, may therefore result in reduced ICAM-1 expression. ICAM-1 depletion leads to M1 macrophage polarization(47), which is the

pro-inflammatory macrophage subtype that promotes an unstable plaque phenotype(48). Reduced OSM signaling could also explain the decreased collagen content as OSM enhances *in vitro* fibroblast proliferation and collagen formation(20). Moreover, it was previously shown that OSM enhances liver fibrosis in mice(49) and that OSM is upregulated in patients with pulmonary fibrosis(50). A reduction in OSM signaling caused by decreased OSMR expression may therefore result in decreased collagen content. Further studies are needed to investigate these hypotheses.

A possible explanation for the lack of associations for the variant (rs10491509) in the *LIFR* locus could be that an increase in *LIFR* expression would not affect OSM signaling as, hypothetically, there might already be a *LIFR* surplus and therefore, an increase in *LIFR* expression will not affect OSM signaling.

Although rs13168867 did associate with plaque vulnerability, no associations were found between rs13168867 and intraplaque *OSMR* expression, intraplaque *OSMR* expression and plaque vulnerability, nor did known *OSMR* eQTLs associate with cardiovascular disease outcomes. Possibly, OSM signaling mainly affects atherogenesis and atherosclerosis development in the initial phases of the disease. Arterial *OSMR* expression is reduced in human atherosclerotic plaques when compared to normal arteries[9] and may therefore have bigger effects in the initial phase, when *OSMR* expression is still high. Another possible explanation is that OSM signaling may be overruled by for example, other cytokines in later stages of the disease.

A limitation of association studies like ours, is that it is challenging to uncover the biological meaning of the discovered associations. It is likely that a reduction in OSMR expression on the arterial wall reduces OSM signaling, but this is difficult to verify. Firstly, OSM signaling is not only dependent on OSMR, but also on the blood OSM levels. If there is no or little OSM present in the blood, there might have been a surplus of OSMR and in this case, there will be no change in OSM signaling. Another possibility is that there is not only a decrease of OSMR expression on the arterial wall, but also a decrease in circulating OSMR levels, which can also bind to OSM and acts as a neutralizer(51), also resulting in no net difference in OSM signaling. Moreover, this study cannot make a distinction between the timing and the duration of OSM signaling, which may differentially affect atherosclerosis development as previous studies have shown that OSM, like IL-6, can act differently in the acute phase than in the chronic phase(8,9,52,53).

Compared to genome-wide association studies that include thousands of individuals, the Athero-Express Biobank Study is relatively small (n=1,443), and, given its design, finite in size. However, it is well suited to examine the effect of common disease-associated genetic variation on plaque morphology and characteristics. Indeed, we estimated the power at ±75% given a MAF=0.40 (approximately the frequency of rs13168867) and relative risk=1.28 (http://csg.sph.umich.edu/abecasis/gas_power_calculator/).

Recent developments in single-cell expression analyses might extend on the present study by investigating which cell types, that are present in the plaque, most abundantly express *OSM, OSMR* and *LIFR.* Furthermore, it would be interesting to investigate if the *OSMR/LIFR* expression ratio correlates with plaque vulnerability and if this ratio might be a predictor of plaque vulnerability.

5. Conclusion

Based on this work we conclude that the variant rs13168867 in the *OSMR* locus is associated with increased plaque vulnerability, but not with coronary calcification or cardiovascular disease susceptibility. Given the multiple testing burden for individual plaque characteristics, it remains unclear through which precise biological mechanisms OSM signaling exerts its effects on plaque morphology, although our data point towards lipid metabolism and extracellular matrix remodeling. However, the OSM-OSMR/LIFR pathway is unlikely to be causally involved in lifetime cardiovascular disease susceptibility as none of the investigated eQTLs associated with cardiovascular diseases.

Conflict of interest

DvK is employed by Quorics B.V., and DT is employed by SkylineDx B.V and Quorics B.V. Quorics B.V. and SkylineDx B.V. had no part whatsoever in the conception, design, or execution of this study, nor the preparation and contents of this manuscript.

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Author contributions

DvK: Conceptualization, Formal analysis, Writing - original draft. IvK: Data curation. AB: Conceptualization, Formal analysis, Writing – review & editing. HP: Writing – review & editing. AvG: Writing – review & editing. GJdB: Conceptualization. FA: Conceptualization. DT: Conceptualization, Writing – review & editing. GP: Conceptualization, Writing – review & editing. SvdL: Conceptualization, Formal analysis, Writing – original draft, review & editing.

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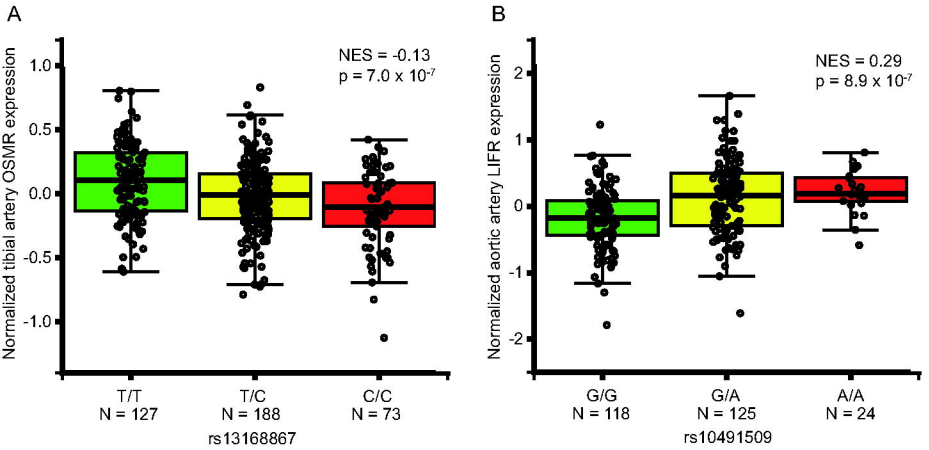
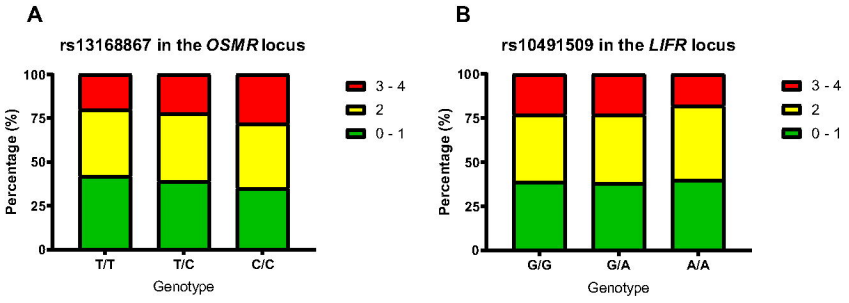

A
Normalized tibial artery OSMR expression
1.0
0.5
0.0
-0.5
-1.0
NES = -0.13
p = 7.0 x 10-7
T/T
N = 127
T/C
N = 188
C/C
N = 73
rs13168867
B
Normalized aortic artery LIFR expression
2
1
0
-1
-2
NES = 0.29
p = 8.9 x 10-7
G/G
N = 118
G/A
N = 125
A/A
N = 24
rs10491509



Gene	Variant	NES	Alleles	EAF	Info	β (s.e.)	*p*
OSMR	rs13168867	-0.13	C/T	0.393	0.999	0.118 (0.040)	**3.00×10^{-3}**
LIFR	rs10491509	0.29	A/G	0.351	0.989	0.001 (0.043)	0.981