Arteriosclerosis, Thrombosis, and Vascular Biology

CLINICAL AND POPULATION STUDIES

High Levels of Complement Activating Enzyme MASP-2 Are Associated With the Risk of Future Incident Venous Thromboembolism

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BACKGROUND: Experimental studies have shown that the complement activating enzyme MASP-2 (mannose-binding lectin associated serine protease 2) exhibits a thrombin-like activity and that inhibition of MASP-2 protects against thrombosis. In this study, we investigated whether plasma MASP-2 levels were associated with risk of future venous thromboembolism (VTE) and whether genetic variants linked to MASP-2 levels were associated with VTE risk.

METHODS: We conducted a population-based nested case-control study involving 410 VTE patients and 842 age- and sex-matched controls derived from the Norwegian Tromsø Study. Logistic regression was used to estimate odds ratios (ORs) of VTE across MASP-2 quartiles. Whole-exome sequencing and protein quantitative trait loci analyses were performed to assess genetic variants associated with MASP-2 levels. A 2-sample Mendelian randomization study, also including data from the INVENT consortium (International Network of Venous Thrombosis), was performed to assess causality.

RESULTS: Subjects with plasma MASP-2 in the highest quartile had a 48% higher OR of VTE (OR, 1.48 [95% CI, 1.06–2.06]) and 83% higher OR of deep vein thrombosis (OR, 1.83 [95% CI, 1.23–2.73]) compared with those with MASP-2 levels in the lowest quartile. The protein quantitative trait loci analysis revealed that 3 previously described gene variants, rs12711521 (minor allele frequency, 0.153), rs72550870 (minor allele frequency, 0.045; missense variants in the *MASP2* gene), and rs2275527 (minor allele frequency, 0.220; exon variant in the adjacent *MTOR* gene) explained 39% of the variation of MASP-2 plasma concentration. The OR of VTE per 1 SD increase in genetically predicted MASP-2 was 1.03 ([95% CI, 1.01–1.05] P=0.0011).

CONCLUSIONS: Our findings suggest that high plasma MASP-2 levels are causally associated with risk of future VTE.

GRAPHIC ABSTRACT: A graphic abstract is available for this article.

Key Words: case-control studies ■ complement ■ deep vein thrombosis ■ humans ■ mannose-binding lectin ■ MASP ■ venous thromboembolism

Venous thromboembolism (VTE), including deep vein thrombosis (DVT) and pulmonary embolism (PE), is a frequent disease affecting 1 to 2 per 1000 individuals annually.[1] VTE is associated with severe complications, including post-thrombotic syndrome, post-PE syndrome, recurrence, and death.[1–3] Although medical thromboprophylaxis is provided to patients at high risk (eg, after major surgery),[4,5] the incidence of VTE has slightly increased over the past decades.[6–8] As the prevalence of major VTE risk factors, such as aging, cancer, and obesity, is increasing,[9–11] the incidence of VTE is expected to continue to increase during the coming years. To lower the burden of VTE in the society, new insights into biomarkers and pathophysiological mechanisms are crucial to improve risk stratification and targeted VTE prevention.

The complement system is an important part of the innate immune system, and several points of

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Nonstandard Abbreviations and Acronyms

BMI	body mass index
CRP	C-reactive protein
DVT	deep vein thrombosis
FVL	factor V Leiden
INVENT	International Network of Venous Thrombosis
MBL	mannose-binding lectin
MR	Mendelian randomization
OR	odds ratio
PE	pulmonary embolism
pQTL	protein quantitative trait loci
SNP	single-nucleotide polymorphism
VTE	venous thromboembolism

Highlights

- In a population-based nested case-control study derived from the Tromsø cohort, high plasma MASP-2 (mannose-binding lectin associated serine protease 2) levels are associated with increased risk of future incident venous thromboembolism.
- According to protein quantitative trait loci analysis, plasma levels of MASP-2 are genetically regulated.
- Mendelian randomization suggests that the association between MASP-2 and venous thromboembolism is causal.

intersection between the complement and coagulation systems may potentially contribute to a prothrombotic phenotype upon complement activation.[12,13] Growing evidence accumulated over the last years suggests that components of the complement system are associated with VTE. Plasma C3 levels are associated with the risk of future VTE in observational studies derived from the general population,[14] and C3-deficient mice displayed lower thrombus frequency and thrombus weight compared with wild-type mice in the inferior vena cava stenosis model.[15] Furthermore, we recently reported that complement activation in vivo, assessed by the measurement of sC5b-9, the soluble form of the terminal complement complex in plasma,[16,17] was associated with risk of future VTE and unprovoked VTE events in particular.[18] These findings suggest that components of the complement system are not only predictive biomarkers of VTE risk but have the potential to be involved in the pathogenesis of the disease.

Pattern recognition molecules of the lectin pathway of the complement system comprise 2 protein families, namely collectins and ficolins. The former includes MBL (mannose-binding lectin), collectin-10, and collectin-11 and the latter ficolin-1, ficolin-2, and ficolin-3. These proteins circulate in the blood in complexes with 3 associated serine proteases named MASPs 1–3 (MBL associated serine proteases; 1–3) and are activated when the pattern recognition molecules bind to particular carbohydrate or acetylated moieties on pathogens or altered host cells.[19,20] We recently reported that subjects with low plasma MBL levels had lower VTE risk.[21] Apart from its canonical role in activating the complement system, both MASP-1 and MASP-2 have the ability to cleave prothrombin to thrombin with subsequent fibrin formation.[20,22-24] While MASP-1 has several substrates in the hemostatic system, including prothrombin, factor XIII, fibrinogen, and thrombin activatable fibrinolysis inhibitor, the activity of MASP-2 seems to be specific toward prothrombin.[25] Hence, the assessment of MASP-2 might provide novel insights into the pathogenesis of VTE that is particularly mediated by thrombin generation, which is probably a key mechanism of venous thrombus formation.[26] Moreover, elevated plasma MASP-2 levels have been reported in patients with acute ischemic stroke compared with healthy controls.[27] Additionally, inhibition of MASP-2 protects against stroke[28,29] and myocardial infarction[30,31] in animal models.

Based on these findings, we hypothesized that elevated plasma MASP-2 levels might be associated with an increased risk of future VTE. In the present nested case-control study derived from the general population comprising 410 VTE patients and 842 age- and sex-matched controls, we aimed to (1) investigate whether plasma MASP-2 levels were associated with risk of future VTE, (2) identify genetic variants that regulated plasma MASP-2 levels, and (3) explore whether these variants were associated with VTE risk in a Mendelian randomization (MR) framework.

METHODS

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Study Population

The Tromsø Study is a population-based cohort with repeated health surveys of residents in the municipality Tromsø in the northern part of Norway.[32] To the fourth survey in 1994 to 1995, all inhabitants aged ≥25 years living in the municipality were invited to participate, and 27 158 subjects participated (77% response rate). These participants formed a cohort and were followed from their survey inclusion date (1994/1995) until September 1, 2007. All first lifetime events of VTE occurring among the participants during follow-up were identified by searching the hospital discharge diagnosis registry, the autopsy registry, and the radiology procedure registry of the University Hospital of North Norway, the sole provider of hospital care in the Tromsø region. Trained personnel systematically reviewed the medical records and recorded each adjudicated VTE

event, as described previously in detail.[33] In brief, an episode of VTE was adjudicated based on the presence of signs and symptoms of DVT or PE in combination with objective confirmation by radiological procedures (compression ultrasonography of the whole leg, venography, computed tomography pulmonary angiogram, perfusion ventilation, pulmonary angiography, or autopsy) that resulted in the initiation of treatment (unless contraindications were specified). A VTE event was further classified as unprovoked or provoked based on provoking factors closely preceding the VTE diagnosis. A VTE occurring in the presence of ≥1 of the following provoking factors was defined as provoked: recent hospitalization, surgery or trauma (within 8 weeks before the event), cancer, acute medical condition (acute myocardial infarction, acute ischemic stroke, acute infections), immobilization (bed rest >3 days, long-distance travel of >4 hours duration during the last 14 days, or confinement to a wheelchair within the last 8 weeks), or other factors described explicitly as provoking by a physician in the medical record (eg, intravascular catheter).

During the cohort follow-up (1994–2007), 462 participants experienced a VTE event. We created a nested case-control study for the assessment of MASP-2 from stored blood samples from this cohort. In a nested case-control study, the temporal sequence between exposure and outcome is preserved, and this design is, therefore, efficient to study biological precursors of disease. For each case, 2 age- and sex-matched controls (n=924), who were alive at the index date of the corresponding VTE case, were randomly sampled from the source cohort (Figure 1). A total of 52 cases and 82 controls were excluded because plasma samples were not available or of inadequate quality for the analyses. Thus, the final study population consisted of 410 cases and 842 controls. All participants provided written consent for participation in the study, and the Regional Committee for Medical and Health Research Ethics approved the study.

Baseline Measurements

Baseline information at inclusion in the fourth survey in the Tromsø Study (1994/1995) was collected by physical examination, blood samples, and a self-administered questionnaire. Height (to the nearest centimeter) and weight (to the nearest 0.5 kg) were measured in participants wearing light clothing and no shoes. Body mass index (BMI) was calculated as weight divided by the square of height in meters (kg/m^2). Information on smoking status, history of cardiovascular disease events (stroke, angina pectoris, transient ischemic attack, and myocardial infarction), diabetes, and cancer were retrieved from the questionnaire.

Blood and DNA Sample Collection and Storage

At inclusion in 1994/1995, nonfasting blood was collected from an antecubital vein into 5-mL vacutainers (Becton Dickinson, Le Pont de Claix, France) containing ethylenediaminetetraacetic acid (K_3-EDTA 40 µL, 0.37 mol/L per tube) as an anticoagulant. Platelet-poor plasma was prepared by centrifugation at 3000*g* for 10 minutes at room temperature, after which the supernatant was transferred into cryovials (Greiner Labotechnik, Nürtingen, Germany) in 1-mL aliquots and stored at −80 °C. DNA isolated from blood was stored at the National CONOR (Cohort of Norway) Biobank.[32]

Measurements of Plasma Levels of MASP-2 and CRP

To measure biomarkers in plasma, samples were thawed in a water bath at 37 °C for 5 minutes, followed by centrifugation for 2 minutes at 13 500*g* to obtain platelet-free plasma.

MASP-2 was measured using a sandwich MASP-2 ELISA (Hycult Biotech, Uden, the Netherlands). The assay was performed according to the instructions from the manufacturer. Optical density was measured using a microplate reader (Infinite M200 pro; Tecan Trading AG, Switzerland). The intra- and inter-assay coefficients of variation were <5% and 12.5%, respectively. Each sample was normalized with respect to a commercially available control provided by the manufacturer, and the global median of MASP-2 levels derived from all control subjects of the nested case-control study. The value of the manufacturer's control obtained in each plate of the MASP-2 ELISA was subtracted from the raw value, and the global median was added ($\text{MASP-2}_{\text{Normalized value}} = \text{MASP-2}_{\text{Raw value}} - \text{MASP-2}_{\text{Control value}} + \text{MASP-2}_{\text{Global median value}}$).

CRP (C-reactive protein) was measured by the high-sensitivity technique in duplicates by enzyme immunoassay using commercially available reagents (R&D Systems, Minneapolis, MN) in a 384 format using the combination of a SELMA (Jena,

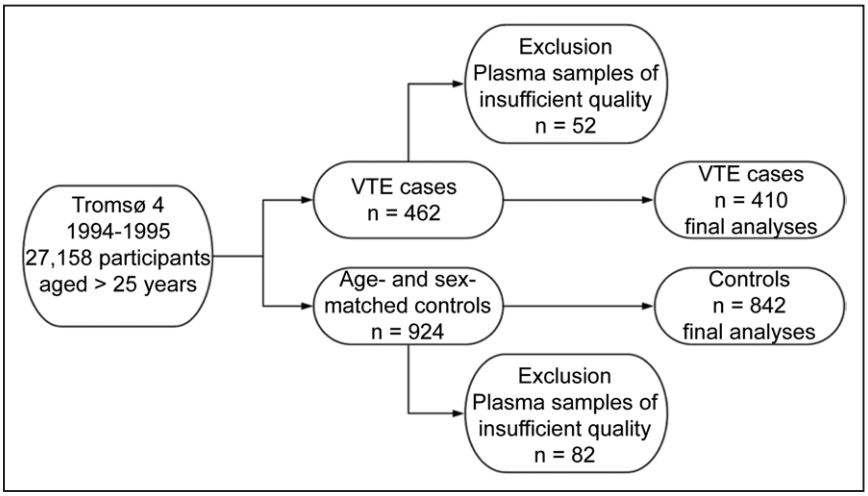

Figure 1. Flowchart of the study population.
The flowchart illustrates the nested case-control study derived from the fourth survey of the Tromsø Study (1994–1995). VTE indicates venous thromboembolism.

Germany) pipetting robot and a BioTek (Winooski, VT) dispenser/washer (EL406). Absorption was read at 450 nm with a wavelength correction set to 540 nm using an enzyme immunoassay plate reader (Synergy H1 Hybrid; BioTek, Winooski, VT). The intra- and inter-assay coefficients of variation were 2.6% and 9.1%, respectively.

Exome Sequencing

Whole-exome sequencing at high coverage (≈100×) was performed in a random subset of the nested case-control study population (353 VTE patients and 354 control subjects) by the use of the Agilent SureSelect 50Mb capture kit. The subsequently retrieved genotypes were effectively filtered[34] and imputations performed as previously described in detail.[35] In brief, using the information from the exome sequencing data, genotypes were imputed to the whole genome using Beagle[36] and haplotypes from unrelated individuals from the European and East Asian superpopulations of the 1000 Genomes Project Phase 3[37] for sites with a minor allele frequency >1%.

Statistical Analysis

Association Between MASP-2 Levels and Risk of VTE in the Nested Case-Control Study

Statistical analyses were performed using Stata, version 16 (StataCorp LLC, College Station, TX), and R, version 4 (The R Foundation for Statistical Computing, Vienna, Austria; https://cran.r-project.org). Plasma MASP-2 was categorized according to quartile cutoffs in the control population (<302, 302–549, 550–823, and ≥824 ng/mL). Means and proportions of baseline characteristics across quartiles of MASP-2 were calculated using descriptive statistics. Logistic regression models were used to estimate odds ratio (OR) of VTE with 95% CIs according to quartiles of MASP-2 adjusted for the matching factors,[38] with the addition of BMI and CRP as adjustment variables in a second model. The lowest quartile of MASP-2 was used as the reference group. *P* values for linear trend across increasing quartiles of MASP-2 were estimated. Separate analyses were additionally conducted with unprovoked VTE, DVT, and PE as outcomes.

Due to the long follow-up time (≥12 years for many individuals) in the source cohort, the results based on baseline MASP-2 measurements could be influenced by regression dilution bias. To address this, we performed analyses that restricted the maximum follow-up time from blood sampling to the VTE events, while keeping all controls in the analyses. The logistic regression analyses on time restrictions were set to require at least 10 VTE events, and ORs were generated at every time point a new VTE event occurred and plotted as a function of this maximum time.

To assess potential nonlinearity between plasma MASP-2 levels and risk of VTE, a generalized additive regression plot was generated to visualize the association by modeling MASP-2 with a smoothing spline fit in a logistic model adjusted for age, sex, BMI, and CRP. We created one plot for the full follow-up and one plot restricted to the first 5 years of follow-up. The MASP-2 levels were transformed to follow a perfect standard normal distribution with a mean value of 0 and an SD of 1 before entering the analyses.

Identification of Single-Nucleotide Polymorphisms Associated With MASP-2 Plasma Levels in the Protein Quantitative Trait Loci Analysis

After filtering and imputation, the whole-exome data set contained 1 033 970 variants. A protein quantitative trait loci (pQTL) analysis was applied to identify genetic variants associated with regulation of MASP-2 plasma levels using samples collected at cohort baseline, when all participants were VTE-free individuals. This pQTL analysis was performed both in a genome-wide setting and restricted to the loci within ±500 kb of the different genes involved in the complement system. The commonly used significance threshold of 5×10^{-8} was used to adjust for multiple testing in the genome-wide setting. As the *cis*-analysis in total contained 11 829 variants, a Bonferroni-based adjustment for multiple testing corresponded to a significance threshold of $-\log_{10}(0.05/11\,829) = 5.37$. The plasma MASP-2 values transformed to follow a perfect standard normal distribution were used in the pQTL analysis. The pQTL analysis was performed with the EPACTS (Efficient and Parallelizable Association Container Toolbox) software.[39] The EMMAX[40] (Efficient Mixed Model Association eXpedited) linear mixed model approach implemented within EPACTS was used to test for associations between MASP-2 and genetic variants while adjusting for covariates (age, sex, BMI, CRP, and VTE status) and genetic relatedness between individuals in the cohort. Because the Tromsø Study, which is the source of our nested case-control study, is a population-based cohort, it may naturally include some proportion of related individuals.[35] Of the 707 exome sequenced individuals, 6% were related to another individual in the study at an identity-by-descent value of 0.1. To search for independent genetic variants, we applied linkage disequilibrium pruning.

Single-Nucleotide Polymorphisms Regulating MASP-2 Levels and Risk of VTE by MR

A 2-sample MR study was performed to investigate the association between MASP-2 levels and risk of VTE from a causal perspective. The effect size of each single-nucleotide polymorphism (SNP) on MASP-2 plasma levels was obtained from the pQTL analysis. We used genome-wide association study summary data from the INVENT consortium (International Network on Venous Thrombosis) meta-analysis, including 30 234 VTE cases and 172 122 controls from 18 studies,[41] to obtain the effect size estimates of the association between the individual SNPs and VTE. For each SNP, the 2 effect sizes (ie, SNP on MASP-2 and VTE) with corresponding SEs were calculated, and based on these effect sizes, the estimated increase in OR of VTE per SD increase in genetically predicted MASP-2 levels was estimated using the inverse-variance weighted method of MRBase.[42] The obtained estimates of the causal inference based on MR were interpreted with the assumptions that the identified SNPs (1) were truly predictive of MASP-2 in study participants, (2) were not associated with confounders that influenced both MASP-2 and VTE risk, and (3) affected VTE risk only through their effects on MASP-2, as described elsewhere.[43]

RESULTS

The distribution of baseline characteristics of the study participants across quartiles of plasma MASP-2 is shown in Table 1. The mean age slightly decreased, while the

Table 1. Distribution of Baseline Characteristics Across Quartiles of Plasma Levels of MASP-2

	Q1 (<302 ng/mL)	Q2 (302–549 ng/mL)	Q3 (550–823 ng/mL)	Q4 (≥824 ng/mL)
n	297	296	315	344
Age, y (±SD)	62.4±14.3	61.4±13.8	59.1±13.7	58.4±13.0
Sex: male, % (n)	41.4 (123)	46.0 (136)	51.1 (161)	49.4 (170)
BMI, kg/m^2	25.9±4.0	26.3±4.2	26.5±4.2	26.9±4.5
Smoking, % (n)	28.3 (84)	30.1 (89)	31.8 (100)	34.3 (118)
hsCRP, mg/L (±SD)	1.43±1.2	1.47±1.3	1.66±1.3	1.87±1.6
WBC, 10^9/L (±SD)	6.89±1.9	6.95±3.1	7.09±1.8	7.09±2.0
CVD, % (n)*	16.5 (49)	18.9 (56)	13.7 (43)	13.7 (47)
Cancer, % (n)*	5.4 (16)	5.4 (16)	4.4 (14)	3.2 (11)
Diabetes, % (n)*	4.7 (14)	3.0 (9)	3.5 (11)	4.1 (14)

BMI indicates body mass index; CVD, cardiovascular disease (history of myocardial infarction, stroke, angina pectoris); hsCRP, C-reactive protein measured by a high sensitive technique; and WBC, white blood cell count.

*Self-reported history of CVD, cancer, or diabetes at baseline.

Table 2. Characteristics of Patients at VTE Diagnosis (n=410)

	Values
Age at VTE, y	67.4±13.6
Sex (male)	48.5 (199)
Deep vein thrombosis	61.7 (253)
Pulmonary embolism	38.3 (157)
Unprovoked VTE	42.0 (172)
Provoked VTE	58.0 (238)
Surgery/trauma	22.4 (92)
Cancer	21.7 (89)
Immobilization	17.8 (73)
Acute medical condition	15.6 (64)
Other factors	3.9 (16)

Values are % (n) or means ±1 SD. VTE indicates venous thromboembolism.

mean BMI and the proportion of smokers slightly increased, with increasing quartiles of plasma MASP-2. The proportion of men was highest in the two upper quartiles. Predictably, the plasma levels of high-sensitivity CRP slightly increased across quartiles of MASP-2 from 1.43±1.2 mg/L in the lowest quartile to 1.87±1.6 mg/L in the highest quartile. The baseline characteristics of VTE cases and controls are shown in Table S1. VTE patients had higher BMI and higher proportion with history of cancer than controls, whereas the proportion of smokers was somewhat lower in cases versus controls. The distribution of raw and normalized values of MASP-2 in cases and controls is shown in Figure S1.

The characteristics of the VTE patients, measured at the time of the VTE event, are shown in Table 2. The mean age at the time of VTE was 67 years, and 49% were men. Of the total VTE events, 62% were DVTs and 38% were PEs, and 42% of the cases were classified as unprovoked.

The ORs of VTE, DVT, and PE across quartiles of plasma MASP-2 levels are shown in Table 3. For overall VTE, the OR increased across quartiles of plasma MASP-2 (*P* for trend, 0.01), with the exception of the second lowest quartile. Subjects with plasma MASP-2 ≥824 ng/mL had a 48% higher OR of VTE compared with those with MASP-2 <302 ng/mL (OR, 1.48 [95% CI, 1.06–2.06]) in the model adjusted for age and sex. Plasma levels of MASP-2 were more strongly associated with the risk of DVT (OR for upper versus lower quartile, 1.83 [95% CI, 1.23–2.73]) than with the risk of PE (OR for upper versus lower quartile, 1.04 [95% CI, 0.64–1.69]). Further adjustment for BMI and CRP did not considerably influence the risk estimates (Table 3). The risk estimates for unprovoked events were essentially similar to those observed for overall VTE, DVT, and PE (Table S2). The addition of smoking as a covariate to the regression models did not virtually change the risk estimates for overall VTE and subgroups (data not shown).

The association between MASP-2 levels, entered as a continuous variable, and risk of VTE is depicted in Figure 2. In the analysis that included the full follow-up time (Figure 2A), the OR of VTE started to increase for MASP-2 levels above the 50th percentile, indicating that the 50th percentile cutoff could be appropriate for assessing VTE risk. However, when the follow-up time was restricted to <5 years from blood sampling to VTE diagnosis, a linear association throughout the continuum of MASP-2 levels was more prominent (Figure 2B). As depicted in Figure 2A and 2B, estimates of VTE risk were imprecise with wide 95% CIs at more extreme levels of MASP-2 due to the limited number of individuals in the analysis.

To consider the possibility of underestimating the true association due to regression dilution bias, we estimated ORs (highest versus lowest quartile of MASP-2) of VTE and subgroups (DVT and PE) as a function of time between blood sampling and the events (Figure 3). The ORs of overall VTE and DVT by high plasma MASP-2 were considerably higher with shortened time between blood sampling and VTE. In contrast, no association was observed between MASP-2 and PE over time (Figure 3).

The results of the pQTL analysis are described in Figure 4 and Figure S2. The pQTL analysis revealed 3 SNPs that were significantly associated with MASP-2 plasma levels at the fixed genome-wide threshold of $P<5\times10^{-8}$. The identified SNPs rs12711521 (minor allele frequency, 0.153) and rs72550870 (minor allele frequency, 0.045) are missense variants in exons of the *MASP2* gene on chromosome 1, while rs2275527 (minor allele frequency, 0.220) is an exon variant in the *MTOR* gene, which is a few genes away from *MASP2* (Figure 4B). The SNPs individually accounted for 25%, 17%, and 16% of the

Table 3. ORs With 95% CIs for VTE, DVT, and PE According to Quartiles of Plasma Levels of MASP-2

Quartiles of MASP-2, ng/mL	Controls	Cases	Model 1, OR (95% CI)	Model 2, OR (95% CI)
Overall VTE				
<302	209	88	Ref	Ref
302–549	210	86	0.97 (0.68–1.38)	0.94 (0.66–1.35)
550–823	211	104	1.17 (0.83–1.65)	1.10 (0.78–1.56)
≥824	212	132	1.48 (1.06–2.06)	1.36 (0.97–1.91)
P for trend			0.01	0.04
DVT				
<302	209	49	Ref	Ref
302–549	210	51	1.04 (0.67–1.60)	1.01 (0.65–1.57)
550–823	211	62	1.25 (0.82–1.91)	1.20 (0.78–1.84)
≥824	212	91	1.83 (1.23–2.73)	1.72 (1.14–2.58)
P for trend			0.001	0.004
PE				
<302	209	39	Ref	Ref
302–549	210	35	0.89 (0.54–1.46)	0.85 (0.52–1.41)
550–823	211	42	1.07 (0.66–1.73)	0.99 (0.61–1.61)
≥824	212	41	1.04 (0.64–1.69)	0.94 (0.57–1.53)
P for trend			0.7	1.0

Model 1: adjusted for age and sex. Model 2: adjusted for age, sex, BMI, and C-reactive protein. DVT indicates deep vein thrombosis; MASP-2, mannose-binding lectin associated serine protease 2; OR, odds ratio; PE, pulmonary embolism; Ref, reference; and VTE, venous thromboembolism.

variance of MASP-2 levels, respectively. Together, these SNPs explained 39% of the variance of MASP-2 in the model adjusted for age, sex, BMI, CRP, and VTE status (adjusted r^2, 0.392; $P<2.2\times10^{-16}$). rs2275527 was linked with rs12711521 with an r^2 of 0.44, and the MR analysis was, therefore, performed with and without inclusion of rs2275527 for sensitivity. The detailed information on the 3 SNPs used in the MR analysis is described in Table S3, along with the effect size estimates and SEs for the SNP-exposure (ie, plasma MASP-2) association and the SNP-outcome (ie, VTE) association obtained from the pQTL and the INVENT consortium,[41] respectively.

The inverse-variance weighted MR analysis revealed a statistically significant association between genetically predicted MASP-2 and VTE. The forest plot of the MR analysis with point estimates (log[OR] per SD of MASP-2) and 95% CIs of causal effect of MASP-2 levels on VTE for each of the 3 identified SNPs is shown in Figure 5. The OR of VTE per 1 SD increase in genetically predicted MASP-2 was 1.03 ([95% CI, 1.01–1.05] *P*=0.0011; Figure 5A). Exclusion of rs2275527 showed essentially similar results (Figure 5B).

DISCUSSION

Plasma MASP-2 levels were associated with risk of future VTE in our nested case-control study derived from a population-based cohort. The risk of VTE increased across quartiles of plasma MASP-2 levels, and subjects with plasma MASP-2 levels in the highest quartile had a 48% higher risk of overall VTE and 83% higher risk of DVT compared with those with MASP-2 levels in the lowest quartile. The ORs for VTE and DVT by elevated plasma MASP-2 were substantially higher when the time between blood sampling and the VTE events was shorter. The risk estimates were modestly attenuated by further adjustments for BMI and CRP. Moreover, when MASP-2 was analyzed as a continuous variable, a linear association with VTE risk was noted, mainly in analyses restricted to the first 5 years of follow-up. In the pQTL analysis, we confirmed 3 previously identified genetic variants associated with plasma MASP-2 levels[44,45] and estimated that these variants explained 39% of the variance of plasma MASP-2 levels. By applying an MR approach, genetically predicted MASP-2 levels were weakly, but significantly, associated with VTE risk. Thus, the present results suggest that plasma MASP-2 levels are genetically regulated and causally associated with the risk of VTE.

Although our observations are unchallenged, circumstantial evidence supports a role of the complement lectin pathway and in particular, MASP-2, in the pathogenesis of VTE. First, as thrombus formation originates in the valvular sinuses of the deep veins in a milieu characterized by severe hypoxia,[46,47] endothelial cells are exposed to oxidative stress, which facilitates binding of MBL or other pattern recognition molecules from the lectin pathway to the endothelial cell surface with subsequent activation of MASP-2.[48-50] Accordingly, we recently reported that the risk of VTE increased with higher plasma MBL levels.[21] Second, in vitro studies have shown that activated MASP-2 can cleave prothrombin to thrombin with subsequent fibrin formation,[20,22,23] and several observational studies have shown that a high degree of coagulation activation is associated with the risk of future VTE.[51-54] Third, experimental studies in mouse models of arterial thrombosis have shown that inhibition of MASP-2, either by genetic deficiency or antibody neutralization, caused smaller myocardial infarct sizes[30,31] and less cerebral infarct volumes and neurological deficits.[28] Supporting these observations, the multiple interactions between the lectin complement pathway and the coagulation system, as well as key complement factors (eg, C3, C5, and the terminal complement complex) that have been shown to associate with the risk of future VTE, are summarized in Figure 6 and Table S4. Furthermore, elevated levels of C3—a central component of the complement system—are

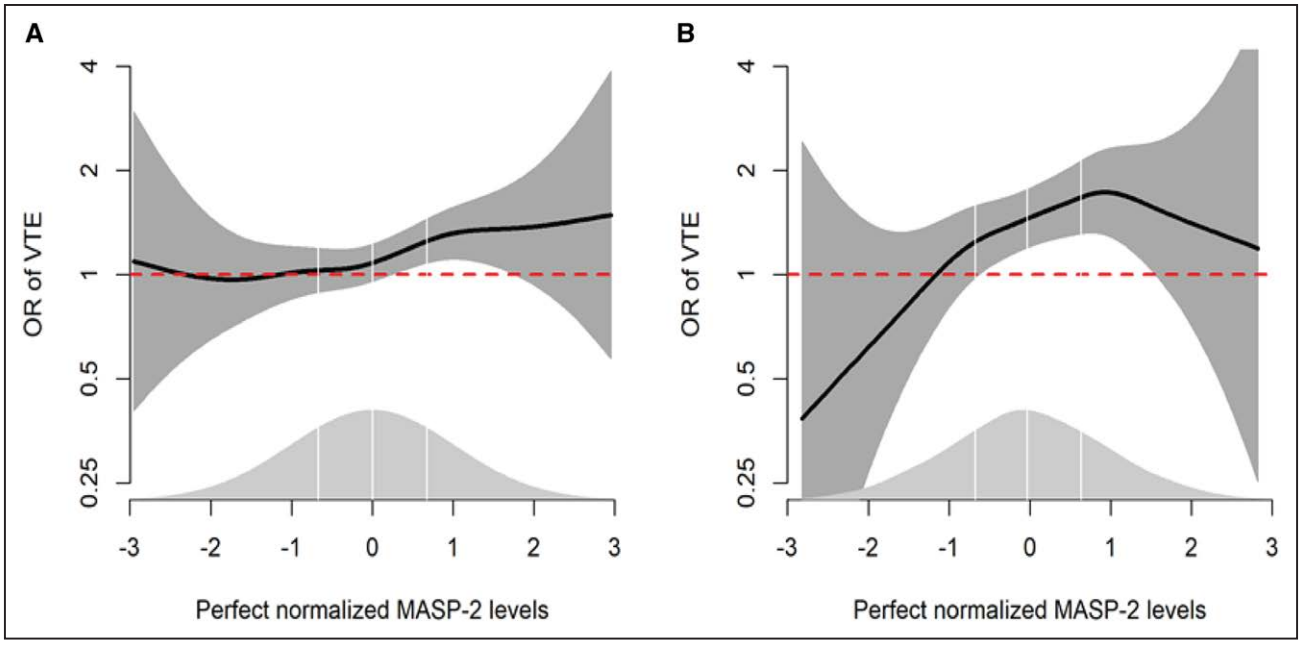

Figure 2. Odds ratios (ORs) of venous thromboembolism (VTE) as a function of MASP-2 (mannose-binding lectin associated serine protease 2) plasma levels adjusted for age, sex, body mass index, and C-reactive protein in a generalized additive regression model.
A, Results for the full follow-up. **B**, Results of analyses restricted to the first 5 years of follow-up. The solid lines show ORs surrounded by shaded areas showing 95% CIs. The distributions of MASP-2 plasma levels are shown as density plots (light gray) at the bottom, and white vertical lines indicate quartile cutoff.

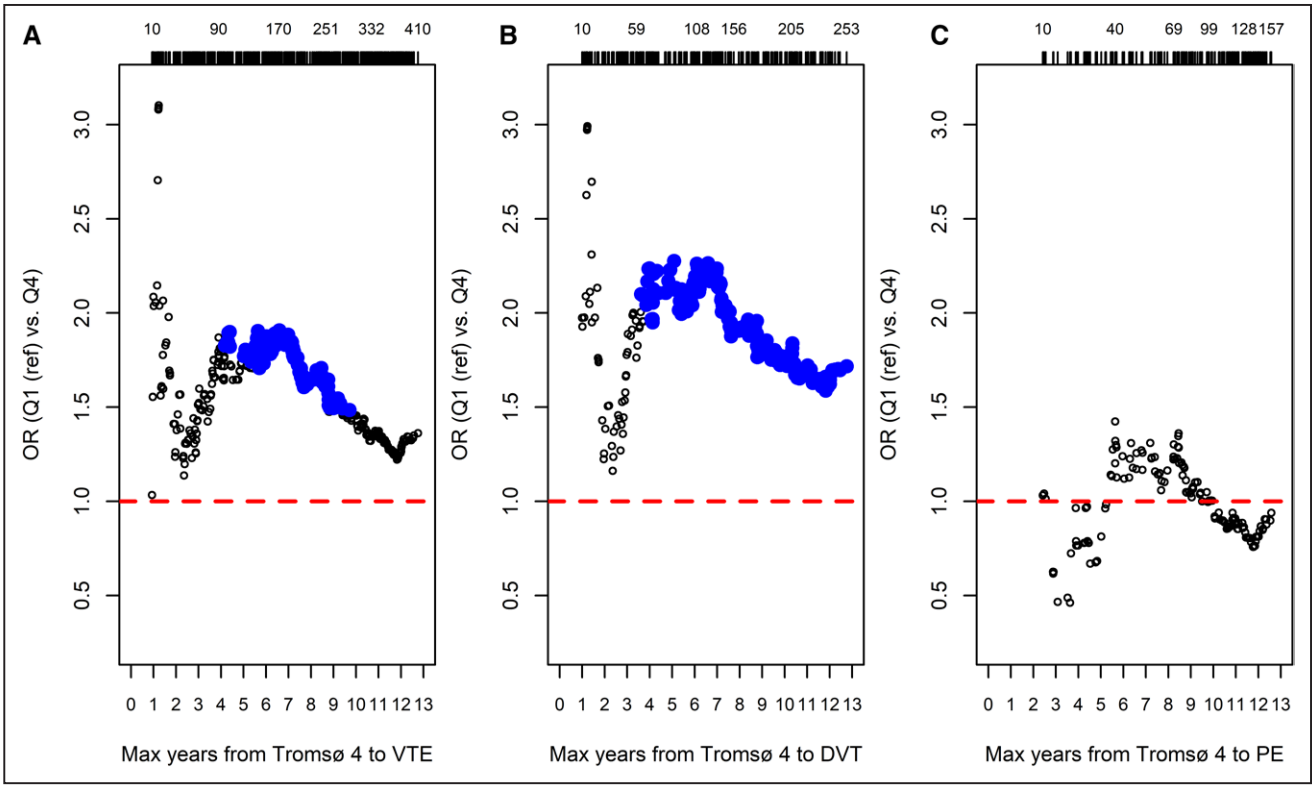

Figure 3. Plots of estimated odds ratios (ORs) of overall venous thromboembolism (VTE), deep vein thrombosis (DVT), and pulmonary embolism (PE) as a function of maximum time from blood sampling in Tromsø 4 (1994–1995) to events.
A, Overall VTE. **B**, DVT. **C**, PE. All analyses were adjusted for age, sex, body mass index, and C-reactive protein. Subjects with plasma MASP-2 (mannose-binding lectin associated serine protease-2) in the highest quartile (Q4) were compared with those with MASP-2 levels in the lowest quartile (Q1, reference category). The number of VTE, DVT, and PE events are depicted above the plot. Large, solid circles indicate ORs with $P<0.05$.

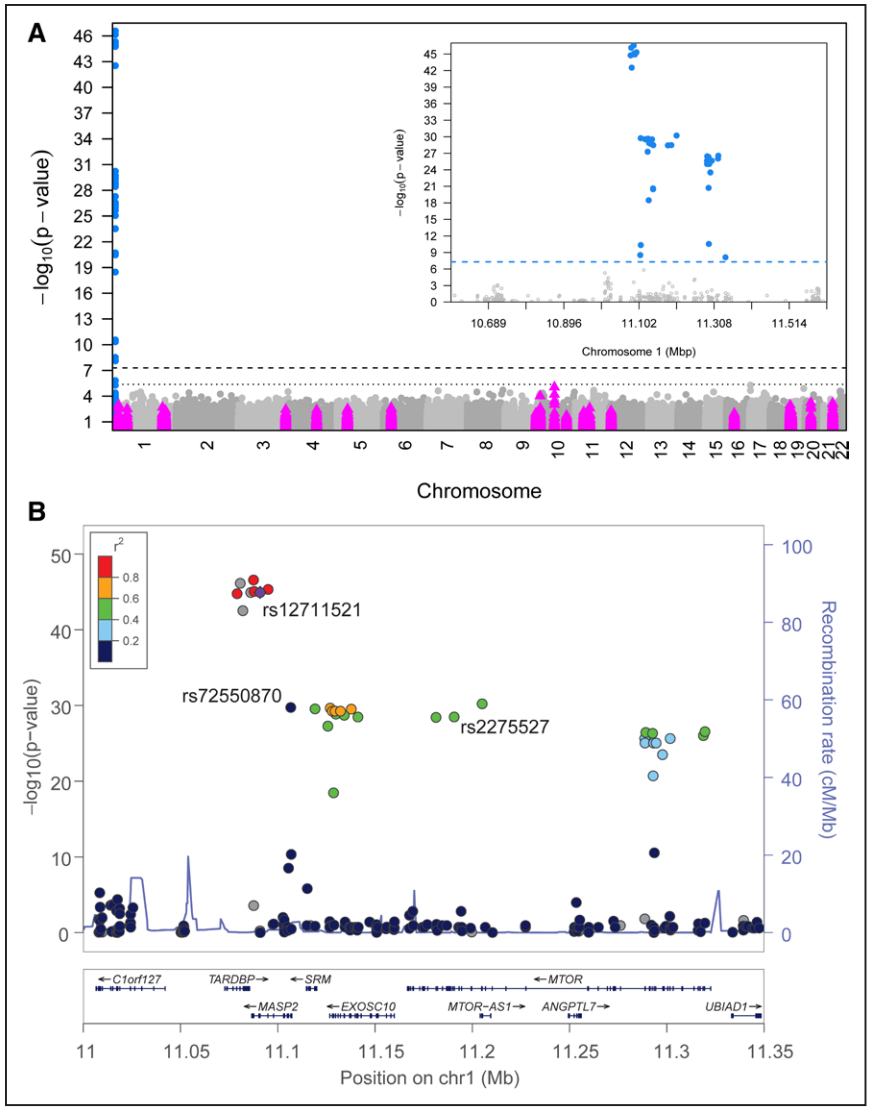

Figure 4. Protein quantitative trait loci (pQTL) analysis results. **A**, Manhattan plot of pQTL analysis (GRCh37/hg19 was used as reference human genome). The upper, dashed line indicates the 5×10^{-8} *P* significance threshold. The purple triangles indicate complement-related genes. In the genome-wide plot, the blue dots are the cis-region around *MASP-2* (mannose-binding lectin associated serine protease-2). In the inserted cis-region plot, those above the genome-wide threshold are marked in blue. **B**, Regional plot for the associated region near *MASP-2* on Chr1, with r^2 value for the linkage disequilibrium of variants. rs12711521 and rs72550870 were independent missense single-nucleotide polymorphisms in the *MASP-2* exons.

associated with cardiovascular risk factors, such as obesity, hypertension, and insulin resistance,[55,56] findings that strengthen the notion of a relationship between the complement system and cardiovascular disease.

In our study, the association between plasma MASP-2 levels and VTE was entirely driven by the relationship between MASP-2 levels and risk of DVT. The explanation for this observation is uncertain but could potentially be related to site of action and involved mechanisms. As the pattern recognition molecule–MASP-2 complexes may bind to the endothelial surface and activate MASP-2 under hypoxic conditions,[47-50] valvular sinuses in the deep veins could be predilection sites for coagulation activation by MASP-2. Furthermore, hypercoagulable states associated with higher risk of DVT than PE, often referred to as the FVL (factor V Leiden) paradox,[57] has been explained by the formation of stable clots less susceptible for embolization. Indeed, an experimental study in mice reported that thrombi in FVL carriers were larger and embolized less than in wild-type mice.[58] Accordingly, our observation of a preponderance of DVT over PE in those with high MASP-2 levels may suggest that MASP-2 activation promotes formation of thrombi less fragile to embolization.

A prerequisite for causal inference of the apparent association between plasma MASP-2 levels and VTE risk is a clear temporal sequence where the presence of the exposure, that is, elevated MASP-2 level, occurs before the outcome, that is, the VTE. In our study, the association between MASP-2 and VTE risk was demonstrated in a nested case-control study—a study design that would not be susceptible to reverse causation.[59] Although multivariable adjustments for potential confounders only modestly attenuated the association between MASP-2 and VTE risk, residual confounding cannot be ruled out due to the observational nature of the study.[60] MR analysis is a method designed to uncover causal relationships between exposure and outcome in observational studies.[61,62] MR exploits the fact that gene variants robustly associated with modifiable exposures

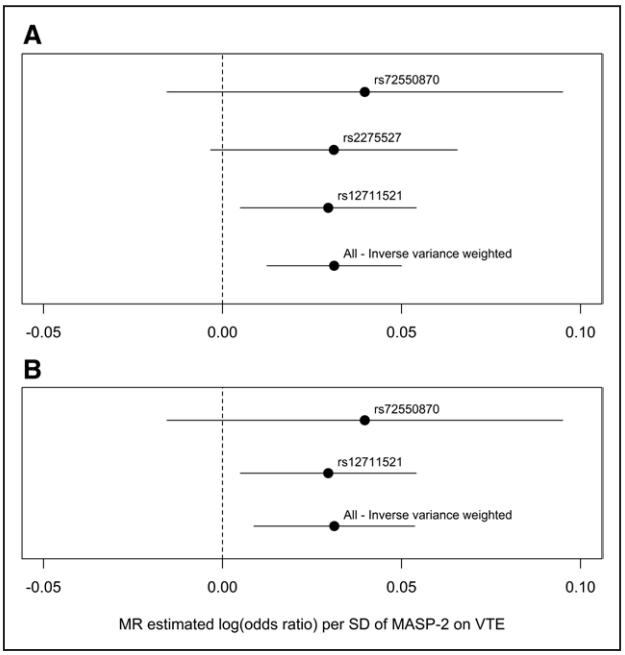

Figure 5. Forest plot of the Mendelian randomization (MR) analysis.
Forest plot of the MR analysis with point estimates (log[odds ratio] per SD of MASP-2 [mannose-binding lectin associated serine protease-2]) and 95% CIs of causal effect of plasma MASP-2 levels on venous thromboembolism (VTE) for each single-nucleotide polymorphism (SNP) and collectively (ie, inverse-variance weighted analysis) in regression analyses. **A**, Forest plot of MR analysis with the inclusion of all 3 SNPs (rs12711521 and rs72550870 in *MASP2* and rs2275527 in *MTOR*). **B**, Forest plot of MR analysis with the exclusion of the SNP in *MTOR* (rs2275527).

are fixed at conception and follow Mendel's laws for inheritance.[61,62] We identified 2 missense mutations in the *MASP2* gene (rs12711521 and rs72550870) and 1 variant in an adjacent gene named *MTOR* (rs2275527). All 3 variants have previously been described,[44,45] and these gene variants explained 39% of the variation of plasma MASP-2 levels in our study. Even after excluding the variant in the adjacent gene (rs2275527), which is partly in linkage disequilibrium with one of the missense mutations in *MASP2* (rs12711521), the remaining variants in the model explained an equal variation of plasma MASP-2 levels. Using summary data obtained from the INVENT consortium,[41] we found that 1-SD increase in genetically predicted MASP-2 showed a weak but significantly increased VTE risk, suggesting a causal relationship between MASP-2 and VTE risk. The MR estimates remained essentially the same upon exclusion of the variant in *MTOR*. Importantly, because rs12711521 and rs72550870 are missense variants in *MASP2*, the risk of biased MR estimates due to horizontal pleiotropy is low, as it is unlikely that these variants would influence VTE through a pathway other than plasma MASP-2. Of note, in previous genome-wide association analyses of VTE involving the genome-wide association study summary data from the INVENT consortium[41] and the Million Veteran Program and UK Biobank,[63] no signal at the *MASP2* locus was detected. In the present study, because the effect size of the association between the SNPs in *MASP-2* and VTE was modest at most (see Table S3 for details), it might be speculated that such association did not reach a genome-wide significant level in the previous genome-wide association study.[41,63] In light of the currently available data, future studies are warranted to confirm our findings from the MR analysis on MASP-2 and VTE.

Although our pQTL analysis confirmed that plasma MASP-2 levels are under a strong genetic regulation,[44,45,64] the OR for VTE according to high versus low MASP-2 levels increased with shorter time between blood sampling and VTE. This implies that biological fluctuations of plasma MASP-2 during the long follow-up resulted in underestimation of the true association—a phenomenon called regression dilution bias.[65,66] In analysis restricted to <5 years from blood sampling to VTE diagnosis, a linear association between MASP-2 levels and VTE risk was displayed throughout the continuum of MASP-2 levels, which reinforces the notion of a biological gradient between plasma MASP-2 levels and risk of VTE. Additionally, we observed a significant, albeit weak association between genetically predicted MASP-2 and VTE in our MR analysis, further strengthening the hypothesis of a causal relationship.

Strengths of this study include the temporal sequence of exposure and outcome in a sample recruited from the general adult population with validated VTE events and access to exome sequencing data and measured plasma MASP-2 levels in the same population. The study also has limitations. Changes in MASP-2 levels during follow-up could result in underestimation of the OR, as indicated by the regression dilution plot showing higher ORs when analyses were restricted to the first years after follow-up. Blood samples were drawn in 1994 to 1995 and stored at −80 °C for up to 22 years. The long storage time could potentially affect the plasma MASP-2 levels. However, plasma MASP-2 levels in our study population were similar to those in previous reports among healthy individuals and blood donors.[67,68] Additionally, as all samples were stored under the same conditions and for the same amount of time for cases and controls, the storage effect is assumed to be similar in the 2 groups, and any misclassification would be nondifferential with regard to VTE status. Even though imputation expanded the investigation beyond the exome and allowed for the identification of variants in intergenic or intronic regions, the power to detect *trans*-acting pQTLs was limited, as described previously.[35] Finally, the limitations of an MR approach[61,62] should be considered when interpreting the results.

In conclusion, the current results indicate that high plasma MASP-2 levels are causally associated with risk of future VTE. Further studies are warranted to confirm

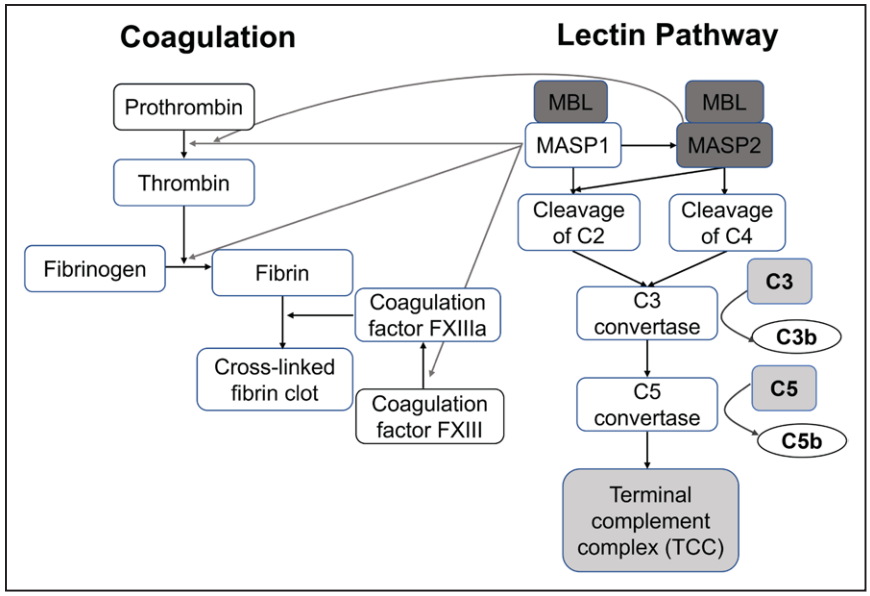

Figure 6. A simplified overview of multiple interactions between factors of the lectin pathway, as well as central factors of the complement system with the coagulation system. The complement factors that have been shown to associate with risk of venous thromboembolism are colored with gray shades (deeper shade for the lectin pathway factors and lighter shade for the factors of the common pathway) and are also summarized in Table S4. Gray arrows indicate activation of coagulation factors by lectin pathway factors. MBL, mannose-binding lectin; MASP, mannose-binding lectin associated serine protease.

our findings and to unravel molecular mechanisms and explore potential targets for intervention.

ARTICLE INFORMATION

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Disclosures

None.

Supplemental Material

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