

From GWAS to TWAS: multi-omics dissection of sepsis uncovers consistent impact of *ATG4B* across tissues

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Sepsis is a life-threatening syndrome resulting from a dysregulated host response to infection, leading to widespread inflammation, tissue injury, and multi-organ dysfunction [1]. It remains a significant global health burden, contributing substantially to morbidity and mortality [2]. The pathogenesis of sepsis is highly complex, involving intricate interactions between host immune responses, genetic predispositions, and environmental factors [3]. Despite extensive genome-wide association studies (GWAS) identifying genetic variants associated with sepsis susceptibility, the genetic basis of the disease remains incompletely understood due to its polygenic nature and the limitations of traditional single-layer approaches [4]. To address this, we employed a multi-omics integration strategy combining GWAS, eQTL, and transcriptome-wide association studies (TWAS) to uncover gene-trait associations and refine candidate genes, thus enhancing our understanding of sepsis pathogenesis and informing potential therapeutic strategies.

Methods. The analysis process is illustrated in Figure 1.

Sepsis GWAS data source. Sepsis data for our study were sourced from the GWAS Catalogue (<https://www.ebi.ac.uk/gwas/home>), with a specific focus on hospital admission cases. We incorporated two curated datasets: one by Butler-Laporte G, which includes 18,931 sepsis cases and 663,531 controls (GCST90270871), and another by Hamilton FW, comprising 11,643 cases and 474,841 controls (GCST90281174). To enhance statistical power and comprehensively assess the genetic associations, we merged these two GWAS datasets and performed a meta-analysis using METAL software (<https://csg.sph.umich.edu/abecasis/Metal/index.html>). This analysis utilised a random-effects model under the inverse variance weighting method – specifically, a multiplicative approach – to accommodate potential heterogeneity between studies.

eQTL files source. The eQTL files were derived from the GTEx V8 dataset, which provides extensive gene expression profiles across 49 distinct tissues sourced from 838 post-mortem donors (https://ftp.ebi.ac.uk/pub/data-bases/spot/eQTL/imported/GTEx_V8). Notably, sample sizes varied considerably among tissues, from as few as 73 samples in the renal cortex to up to 706 in skeletal muscle.

TWAS analyses in cross-tissue. In our cross-tissue transcriptome-wide association study (TWAS), we utilised the UTMOST framework (<https://github.com/Joker-Jerome/UTMOST?tab=readme-ov-file>) to assess overall gene–trait associations at the organismal level. This methodology facilitated the identification of additional genes in tissues with enriched

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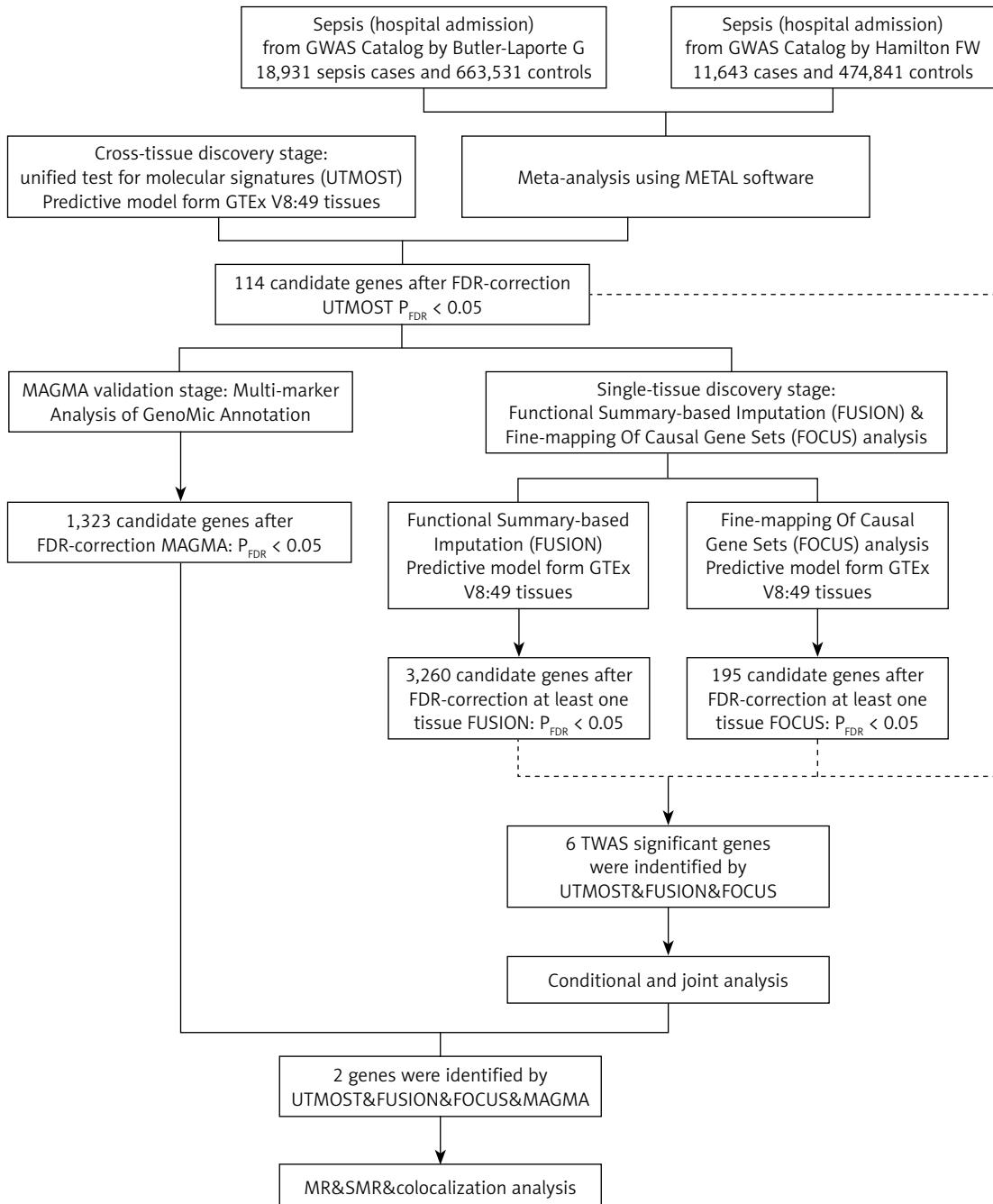
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**Figure 1.** The flowchart of this study

GWAS – genome-wide association, GTEx – Genotype-Tissues Expression Project, TWAS – transcriptome-wide association studies, UTMOST – unified test for molecular signatures, FUSION – functional summary-based imputation, FOCUS – Fine-mapping Of Causal Gene Sets analysis – MAGMA – multi-marker Analysis of GenoMic Annotation.

trait heritability and improved the accuracy of gene expression imputation [5]. Furthermore, we integrated the gene–trait association signals using the generalised Berk-Jones (GBJ) test, which leverages covariance information derived from single-tissue analyses [5, 6]. Statistical significance was determined by applying a false discovery rate (FDR) correction, and associations achieving an FDR threshold of < 0.05 were considered statistically significant.

TWAS analyses in single tissue. To assess the association between gene expression and sepsis risk on a tissue-specific basis, we employed the FUSION tool (<http://gusevlab.org/projects/fusion/>). This approach integrates sepsis GWAS data with eQTL information from GTEx V8 covering 49 tissues, thereby allowing us to estimate the contribution of each gene to disease susceptibility. Initially, the linkage disequilibrium (LD) between the prediction model and the SNPs at each GWAS

locus was calculated using European samples from the 1000 Genomes Project. Subsequently, FUSION combined several predictive models – namely, BLUP, BSLMM, LASSO, Elastic Net, and the top-1 method – to assess the overall impact of SNPs on gene expression. The model that exhibited the highest predictive performance was then chosen to determine the final gene weights. Finally, these gene weights were integrated with the sepsis GWAS Z-scores to perform the transcriptome-wide association study (TWAS). For further analysis, candidate genes were selected based on meeting two criteria: (1) a false discovery rate (FDR) of less than 0.05 in the cross-tissue TWAS analysis, and (2) an FDR of less than 0.05 in at least one tissue in the single-tissue TWAS analysis.

Fine-mapping of causal gene sets (FOCUS) analysis. In addition, we conducted a FOCUS analysis to further refine the identification of causal genes underlying the TWAS signals (<https://github.com/mancusolab/ma-focus>). FOCUS (fine-mapping of causal gene sets) is a probabilistic fine-mapping method specifically designed to accurately discern causal genes from TWAS data. This approach overcomes the limitations inherent in traditional methods, particularly those arising from linkage disequilibrium (LD) and the influence of pleiotropic SNPs. By modelling the correlation structure of gene expression prediction, FOCUS effectively extracts a set of candidate causal genes associated with complex traits and diseases, providing a highly credible prioritisation for downstream gene validation and functional studies. In the present study, the significance thresholds were set such that genes falling within the 90% confidence interval and exhibiting posterior probability values ≥ 0.9 were considered statistically significant [7].

Conditional and joint analysis. In FUSION, it is common to detect multiple associated features within a single locus, prompting the need to assess their conditional independence. To address this, we performed a conditional and joint (COJO) analysis using the post-processing module in FUSION [8]. This approach accounts for the linkage disequilibrium (LD) between markers, thereby providing a more nuanced understanding of the genetic architecture underlying trait variation. Post-analysis, genes that retained significance after accounting for the LD structure were deemed jointly significant, while those that lost significance were classified as marginally significant.

Gene analysis. For our gene-level analysis, we applied MAGMA software (version 1.08) using default settings. This approach aggregates SNP-level association statistics into composite gene scores, thereby quantifying the degree to which each

gene is associated with the phenotype [9, 10]. For a detailed discussion of the parameter settings and methodological framework underpinning this analysis, readers are encouraged to consult the original MAGMA documentation.

Mendelian randomisation and Bayesian colocalisation. We conducted Mendelian randomisation (MR) analysis using the “TwoSampleMR” R package. In this analysis, cis-eQTL SNPs were employed as instrumental variables (IVs), with gene expression serving as the exposure and sepsis GWAS as the outcome. Initially, genome-wide significant SNPs ($p < 5 \times 10^{-5}$) were selected, and linkage disequilibrium (LD) clumping ($r^2 < 0.001$) was performed to retain independent variants. Due to the availability of only a single standalone IV, the MR effect was estimated using the Wald ratio, applying a significance threshold of $p < 0.05$. Additionally, we applied summary-data-based Mendelian randomisation (SMR) to evaluate the relationship between gene expression and sepsis risk. This method leverages the most significant cis-eQTL – identified within a ± 1000 kb window around each gene and meeting the stringent significance threshold ($p < 5.0 \times 10^{-8}$) – to achieve greater statistical power than conventional MR when exposure and outcome data derive from large, independent samples [11]. Variants exhibiting allele frequency differences greater than 0.2 between any pair of datasets (i.e. the LD reference panel, QTL summary, and outcome summary) were excluded from the analysis. The HEIDI test was then employed to distinguish pleiotropy from linkage; SNPs with P-HEIDI values below 0.01 were removed because they were deemed likely to be reflective of pleiotropy. Both SMR and HEIDI analyses were performed using SMR software (v1.3.1). To control the false discovery rate (FDR) at $\alpha = 0.05$, p -values were adjusted using the Benjamini-Hochberg method, and only associations with an FDR-corrected p -value below 0.05 and a P-HEIDI exceeding 0.01 were considered statistically significant.

Subsequently, a Bayesian colocalisation analysis was carried out using the “coloc” R package to determine whether causal variation loci overlapped between the GWAS and eQTL signals. This analysis assessed the posterior probabilities (PP) corresponding to five models. In our colocalisation analysis, a posterior probability of H4 (PPH4) greater than 0.70 was used as supporting evidence for colocalisation. This threshold, which corresponds to a false discovery rate (FDR) of $< 5\%$, strengthens the evidence for a causal relationship between the GWAS and eQTL signals.

Results. TWAS analyses in cross-tissue and single tissue. In the cross-tissue TWAS analysis, 617 genes reached nominal significance ($p < 0.05$)

(Supplementary Table SI), among which 114 genes remained significant after adjustment for multiple testing (FDR < 0.05) (Supplementary Table SI). For the single-tissue TWAS validation, 3260 genes with FDR < 0.05 in at least one tissue were identified (Supplementary Table SII). In parallel, our FOCUS analysis pinpointed 195 genes exhibiting significant associations with sepsis (Supplementary Table SIII). These genes were prioritised based on their high posterior probability scores, which suggest their potential roles as causal drivers in sepsis pathogenesis. By applying these stringent criteria to these analyses, we ultimately identified 6 candidate genes that demonstrated robust associations across cross-tissue and single-tissue analyses. All these genes are protein-coding (*LRRC66*, *RASL11B*, *ATG4B*, *RPL3*, *SGCB*, *THAP4*) (Supplementary Table SIV).

COJO analysis. The 6 candidate genes, predominantly located on chromosomes 2, 4, and 22, were subjected to conditional and joint (COJO) analysis in their respective tissues to mitigate false positive associations that may arise from linkage disequilibrium (LD) (Supplementary Table SV). Specifically, in lung tissue, conditioning on *ATG4B* expression did not appreciably alter the TWAS signal for *RP11-367H1.1* (Supplementary Figure S1 A). Likewise, in brain cerebellum, *ING5*'s association remained largely unchanged after adjustment for *ATG4B* (Supplementary Figure S1 B), and similar stability was observed for *DTYMK* in muscle skeletal (Supplementary Figure S1 C) and *THAP4* in stomach (Supplementary Figure S1 D). These findings suggest that the marginally significant signals at this locus are not driven by *ATG4B*'s predicted expression. In brain anterior cingulate cortex BA24, conditioning on the predicted expression of both *RASL11B* and *DANCR* produced

only a modest reduction in *ERVMER34-1*'s TWAS signal (Supplementary Figure S1 E), indicating that *ERVMER34-1* retains a degree of independent association at this locus.

Analysis of MAGMA. MAGMA gene-based analysis identified 1323 significant genes associated with sepsis (FDR < 0.05) (Supplementary Table SV, Supplementary Figure S2). To further enhance the robustness of our findings, we integrated UTMOST cross-tissue results with the significant genes identified via FUSION, FOCUS, and MAGMA. This comprehensive integration ultimately resulted in the identification of two promising candidate genes, *ATG4B* and *THAP4* (Figure 2), that warrant further investigation as key regulators in sepsis. For the genomic locus 2:242149921–2:243188920, *ATG4B* demonstrated a posterior probability ranging from 0.933 to 1 across 22 tissues – including adipose subcutaneous, adrenal gland, artery aorta, brain cerebellar hemisphere, and colon sigmoid, among others (Supplementary Figure S3 A–3V) – while *THAP4* achieved a posterior probability of 0.961 in the brain hippocampus (Supplementary Figure S3 W).

MR and colocalisation results. The *ATG4B* gene, located on chromosome 2q37.3, emerged as a key candidate in our multi-omics analyses. FUSION analysis demonstrated that *ATG4B* was significantly associated with sepsis across 27 tissues – including adipose subcutaneous, adrenal gland, brain cerebellum, lung, thyroid, uterus, and whole blood – highlighting its broad impact on the sepsis phenotype. MR analysis further supported this association by revealing significant effects in seven tissues (adipose subcutaneous, adrenal gland, adipose visceral (omentum), artery tibia, artery aorta, brain cerebellar hemisphere, and brain cerebellum), with odds ratios ranging from 1.12 to 1.34 (Figure 3). Complementary results were obtained via SMR analysis, which identified significant associations of *ATG4B* with sepsis in 14 tissues, including colon_, nerve tibial, lung, thyroid, pituitary, and whole blood, with odds ratios between 1.12 and 1.37 (Figure 4, Supplementary Table SVIII). Subsequent colocalisation analysis provided further evidence of a causal relationship. *ATG4B* exhibited significant colocalisation effects in 6 tissues – including nerve tibial, colon transverse, whole blood, pituitary, thyroid and colon – sigmoid – with posterior probability of H4 (PP.H4) values ranging from 0.72 to 0.99 (Supplementary Table SVII). Notably, the single nucleotide polymorphism (SNP) rs6720490 emerged as the most significant colocalisation locus in tissues such as nerve tibial, colon transverse, whole blood, and pituitary (Figures 5 A–D). In parallel, rs34968397 was identified as the top colocalisation locus in thyroid and colon - sigmoid (Figures 5 E, F). Col-

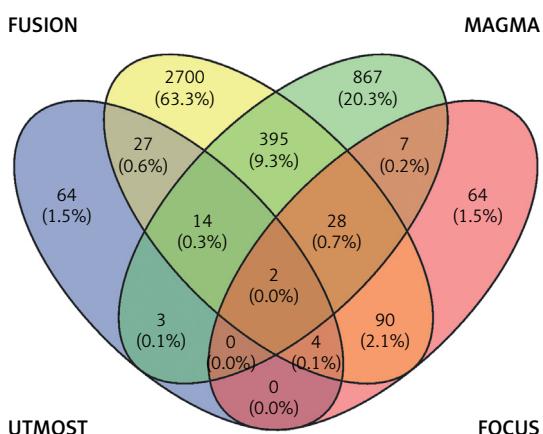
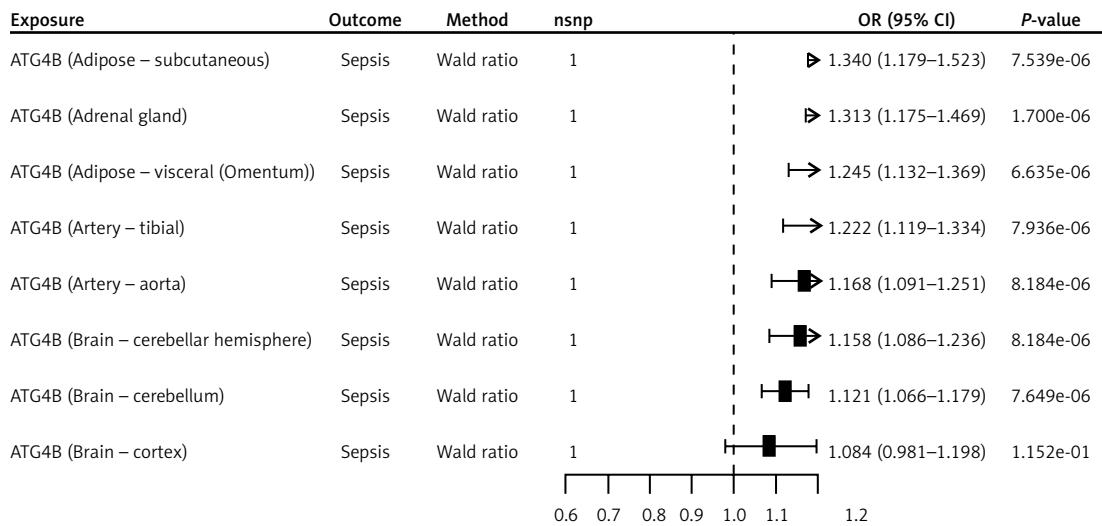


Figure 2. Venn diagram. MAGMA identified 1323 significant genes associated with sepsis, FUSION identified 3260, UTMOST cross-tissue analysis identified 114, and FOCUS identified 195, of which 2 were common

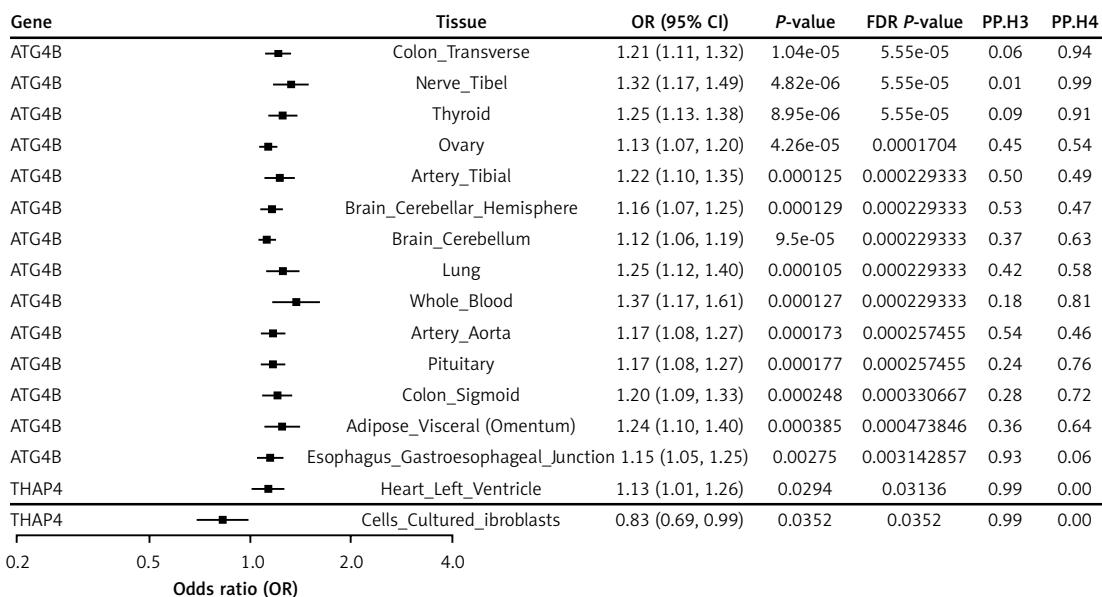
**Figure 3.** The MR results of *ATG4B* with sepsis

lectively, these results underscore the potential of *ATG4B* as a crucial regulator in sepsis pathogenesis and warrant further functional validation.

The *THAP4* gene, also located on chromosome 2q37.3, exhibited significant expression in cells cultured fibroblasts, heart left ventricle, and stomach, according to the FUSION results. Due to insufficient instrumental variables, Mendelian randomisation analysis could not be conducted for *THAP4*, limiting our investigation to SMR analysis. Notably, the effect direction of *THAP4* on sepsis risk was inconsistent across tissues. In heart left ventricle tissue, the SMR analysis yielded an odds ratio (OR) of 1.13 (95% CI: 1.01–1.26), suggesting a risk-enhancing effect, whereas in cells cultured fibroblasts the OR was 0.83 (95% CI: 0.69–0.99), indicating a protective effect (Figure 4, Supplementary Table SVIII). Furthermore, colocalisation

analysis did not detect a significant colocalisation effect in any of these tissues (Supplementary Table SVII), which reduces the certainty of a causal relationship for *THAP4* in sepsis.

Discussion. Our study employed a comprehensive multi-omics approach that integrated GWAS, TWAS (both cross-tissue and single-tissue), conditional and joint (COJO) analysis, gene-based testing using MAGMA, fine-mapping via FOCUS, MR, and SMR, and Bayesian colocalisation analysis. This integrative strategy allowed us to leverage diverse datasets and analytical methods to comprehensively assess the genetic architecture underlying sepsis. Through the cross-tissue and single-tissue TWAS analyses, we initially identified 2 candidate genes that exhibited robust associations with sepsis. These candidate genes were selected based on stringent statistical criteria across

**Figure 4.** The SMR results of two candidate genes with sepsis

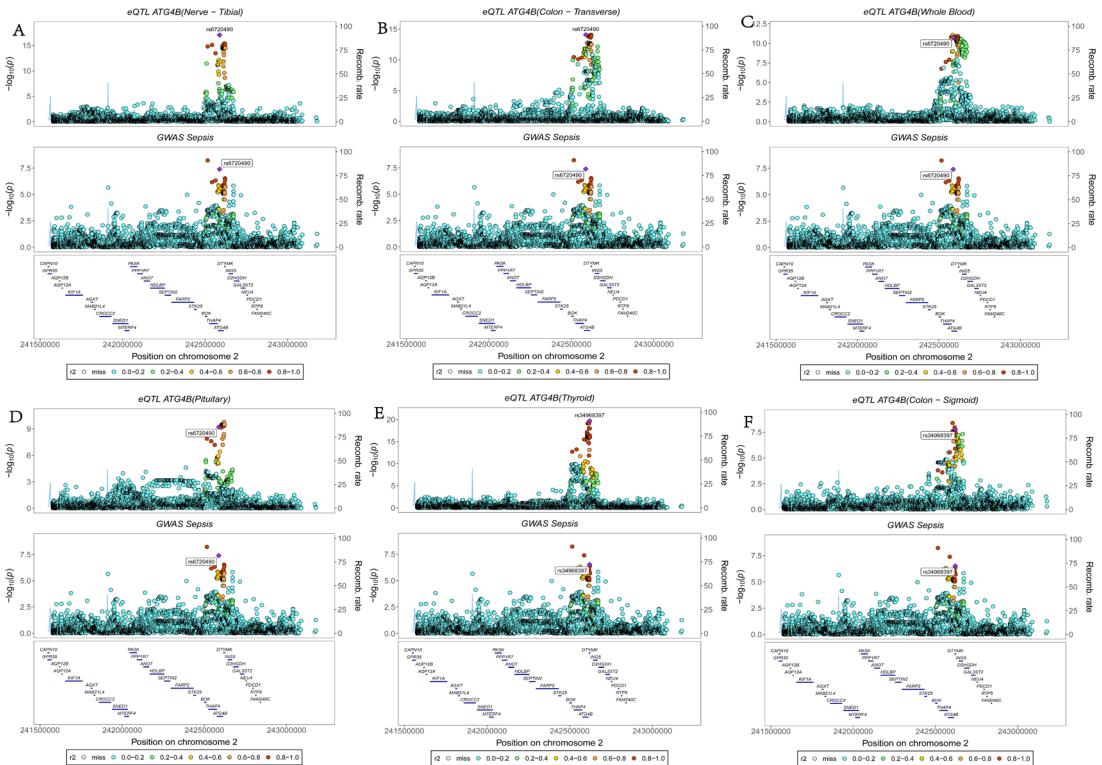


Figure 5. The results of colocalisation analysis between *ATG4B* and sepsis. The SNP rs6720490 exhibited the lowest cumulative sum of sepsis GWAS and *ATG4B* eQTL p values in nerve tibial (A), colon transverse (B), whole blood (C), and pituitary (D). The SNP rs34968397 exhibited the lowest cumulative sum of sepsis GWAS and *ATG4B* eQTL p values both in thyroid (E) and colon sigmoid (F)

multiple tissues, underscoring their potential biological relevance in the pathogenesis of sepsis. The integration of results from UTMOST, FUSION, FOCUS, and MAGMA further refined our candidate gene set, ultimately pinpointing two particularly promising genes – *ATG4B* and *THAP4* – as key regulators. *ATG4B*, in particular, demonstrated consistent and significant associations across numerous tissues along with strong supporting evidence from MR, SMR, and colocalisation analyses. In contrast, *THAP4* exhibited significant expression in selected tissues but showed inconsistent effect directions and lacked robust colocalisation, suggesting that further investigation is warranted.

ATG4B is located on chromosome 2q37.3 and emerged as a noteworthy candidate based on its extensive and significant expression profile across multiple tissues, as demonstrated by our FUSION analysis. The gene was significantly associated with sepsis in as many as 27 tissues, including critical ones such as adipose subcutaneous, adrenal gland, brain cerebellum, lung, thyroid, uterus, and whole blood. This broad tissue expression underscores its potential widespread role in modulating the sepsis phenotype. Both MR and SMR analyses provided strong supportive evidence for the involvement of *ATG4B* in sepsis. MR analysis revealed significant associations in seven tissues

(adipose subcutaneous, adrenal gland, adipose visceral, artery tibia, artery aorta, brain cerebellar hemisphere, and brain cerebellum), with odds ratios ranging from 1.12 to 1.34. Meanwhile, SMR analysis confirmed significant associations in 14 tissues, including colon transverse, nerve tibial, lung, thyroid, pituitary, and whole blood, with odds ratios between 1.12 and 1.37. The consistency of these findings across different tissues and methodologies bolsters the hypothesis that *ATG4B* plays a causal role in sepsis pathogenesis. Further supporting the causal role of *ATG4B*, our colocalisation analysis revealed significant overlap between sepsis GWAS and eQTL signals for this gene, with posterior probability of H4 (PP.H4) values ranging from 0.72 to 0.99 across 11 tissues, including nerve tibial, colon transverse, spleen, thyroid, brain – nucleus accumbens (basal ganglia), and whole blood. The PP.H4 values exceeding the threshold of 0.70 indicate a strong likelihood that the same genetic variants underlying the expression of *ATG4B* are also responsible for the sepsis phenotype, thereby providing robust statistical support for its causal relationship. rs6720490 was identified as the most significant colocalisation locus in tissues such as nerve tibial, colon transverse, whole blood, oesophagus mucosa, and pituitary. Its repeated appearance across

multiple tissues underscores its potential impact on *ATG4B* expression and, by extension, sepsis susceptibility. rs56306534 was highlighted as a top colocalisation signal in spleen, brain – nucleus accumbens, breast – mammary tissue, muscle – skeletal, and pituitary, suggesting that this locus may influence *ATG4B*-mediated pathways in a tissue-specific manner. rs34968397 emerged as the most significant signal in thyroid and colon sigmoid, further validating the gene's role and emphasising the regional specificity of its regulatory influence. Importantly, the prioritisation of *ATG4B* was not based solely on its cross-tissue TWAS significance. Instead, convergent evidence from fine-mapping, conditional analysis, Mendelian randomisation, SMR, and Bayesian colocalisation analyses collectively supports a putative causal role of *ATG4B* in sepsis susceptibility.

THAP4 is located on chromosome 2q37.3 and exhibits significant expression in a select set of tissues, as highlighted by our FUSION analysis. Notably, it demonstrated marked expression in cells cultured fibroblasts, heart left ventricle, and stomach, suggesting a potential tissue-specific role in influencing sepsis susceptibility. Unlike *ATG4B*, MR analysis for *THAP4* could not be performed due to the lack of sufficient instrumental variables. This limitation restricts the direct inference of a causal relationship through MR, thereby necessitating reliance on alternative approaches such as SMR to evaluate its association with sepsis. The SMR analysis yielded conflicting effect directions for *THAP4* across different tissues. In heart left ventricle tissue, the gene exhibited a risk-enhancing effect (OR = 1.13, 95% CI: 1.01–1.26), whereas in cells cultured fibroblasts it showed a protective effect (OR = 0.83, 95% CI: 0.69–0.99). These inconsistencies in the effect size and direction reduce the confidence in a uniform biological impact of *THAP4* on sepsis risk across tissues. Furthermore, the colocalisation analysis did not reveal significant overlap between the sepsis GWAS and eQTL signals for *THAP4* in the tissues examined. The lack of robust colocalisation evidence further diminishes our confidence regarding a causal role for *THAP4* in sepsis pathogenesis.

Multi-omics analyses identify *ATG4B* as a key candidate in sepsis, with consistent associations across multiple tissues, suggesting a mechanistic role in autophagy, inflammation, and stress responses [12, 13]. *ATG4B* is involved in autophagosome formation, essential for cellular homeostasis and recycling damaged organelles. Dysregulation of *ATG4B* may impair autophagic flux, exacerbating inflammation and cellular stress during sepsis [14]. These findings highlight *ATG4B* as a potential therapeutic target. *THAP4*, a member of the *THAP* family, is implicated in transcriptional regulation

and apoptosis [15]. While it shows significant expression in specific tissues, its inconsistent effects across tissues suggest a context-dependent role in sepsis. Further research into the molecular mechanisms of *THAP4* is needed to determine its potential as a therapeutic target in sepsis.

Our study demonstrates the value of integrating analytical methods like UTMOST, FUSION, FOCUS, and MAGMA to explore sepsis genetics, improving candidate gene identification and reducing false positives. While *ATG4B* and *THAP4* emerged as promising regulators, limitations such as insufficient MR instrumental variables, tissue sample size variations, and potential confounders need consideration. Further validation is required to confirm these findings and better understand the molecular mechanisms of sepsis pathogenesis.

In conclusion, our multi-omics approach suggests a potential role of *ATG4B* in autophagy, inflammation, and stress responses in sepsis, supported by consistent tissue associations and MR/SMR analyses. Although *THAP4* showed tissue-specific expression, its inconsistent effects and limited colocalisation require further investigation. Additional experimental validation is needed to confirm these genes as therapeutic targets for sepsis.

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Ethical approval

Not applicable.

Conflict of interest

The authors declare no conflict of interest.

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