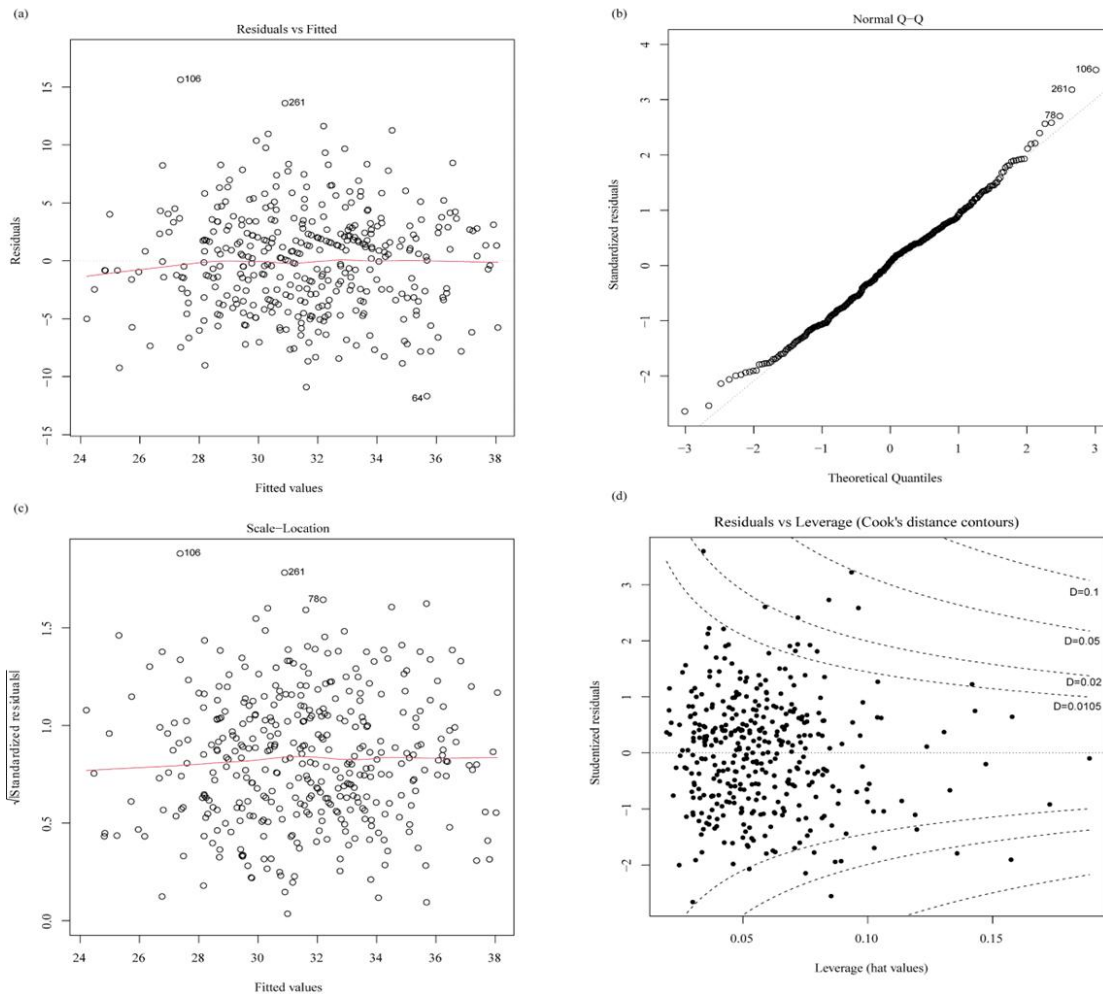


Supplementary Figure 1 Directed acyclic graph depicting the hypothesised relationships between serum 25(OH)D and the FT3/FT4 ratio, with adiposity and inflammation as potential intermediates. Directed acyclic graph (DAG) illustrating the assumed causal structure for the association between serum 25-hydroxyvitamin D [25(OH)D] (exposure, yellow) and the FT3/FT4 ratio (outcome, blue). Age, sex, smoking, alcohol consumption, and season (nodes shown in pink/grey) are included as variables that may influence 25(OH)D and/or the outcome and thus represent potential sources of confounding. Adiposity and inflammation (right-side nodes) are shown as post-exposure variables on the hypothesised pathway linking 25(OH)D to the outcome. Green arrows indicate hypothesised effect/mediation pathways of primary interest, whereas pink arrows denote potential confounding paths considered when selecting covariates for multivariable models.



Supplementary Figure 2 Diagnostic plots for the fully adjusted multivariable linear regression model (model 3). The Figure shows standard diagnostics for the fully adjusted multivariable linear regression model (Model 3; complete-case dataset). (a) Residuals vs Fitted assesses linearity and potential model misspecification; the red line is a LOESS smooth. (b) Normal Q-Q evaluates the normality of standardized residuals. (c) Scale-Location examines homoscedasticity (constant variance) across fitted values. (d) Residuals vs Leverage displays studentized residuals against leverage (hat values) with Cook's distance reference contours ($D = 4/n$, 0.02, 0.05, and 0.10) to highlight potentially influential observations; labeled points correspond to the most influential cases under the default diagnostics.

Supplementary Table 1 Missingness of analysis variables in the study cohort ($n = 1408$)

Variable	Missing (n)	Missing (%)
Age	0	0
Sex	0	0
BMI	0	0
SBP	0	0
DBP	0	0
HbA1c	528	37.5%
TC	273	19.38%
HDL-C	273	19.38%
LDL-C	273	19.38%
TG	273	19.38%
eGFR	333	23.65%
UA	327	23.22%
AST	143	10.15%
ALT	287	20.38%
CRP	275	19.53%
WBC	335	23.79%
VFA	228	16.19%
SFA	227	16.12%
current smoking	95	6.75%
current drinking	97	6.89%
25(OH)D	137	9.7%

Missingness is reported for each analysis variable in the study cohort ($n = 1408$). Missing (n) indicates the number of participants without an available value for the variable; Missing (%) is calculated using 1,408 as the denominator. Current smoking and current drinking refer to self-reported current status (yes/no) as recorded in the case report form; missing values

indicate that the status was not recorded/unknown. Participants with missing 25(OH)D were excluded from analyses involving vitamin D, yielding an analytic sample of $n = 1271$. BMI: Body mass index; DBP: Diastolic blood pressure; SBP: Systolic blood pressure; HbA1C: Glycated hemoglobin; TC: Total cholesterol; HDL-C: High-density lipoprotein cholesterol; LDL-C: Low-density lipoprotein cholesterol; TG: Triglycerides; eGFR: Estimated glomerular filtration rate; UA: Uric acid; AST: Aspartate aminotransferase; ALT: Alanine aminotransferase; CRP: C-reactive protein; WBC: White blood cell count; VFA: Visceral fat area; SFA: Subcutaneous fat area; 25(OH)D: 25-hydroxyvitamin D.

Supplementary Table 2 Association between clinically defined serum 25-hydroxyvitamin D categories and FT3/FT4×100 in multivariable linear regression models

Exposure	Crude (model 1) n=1271	model Partially adjusted model n=1271	adjusted (model 2) n=1271	Fully adjusted model (model 3) n=577
	β (95% CI)	p -value	β (95% CI)	p -value
25(OH)D	0.045 (0.011, 0.079)	0.01043	0.058 (0.022, 0.093)	0.00163
				0.088 (0.037, 0.139)
25(OH)D categories				
< 20	reference		reference	reference
20–30	0.755 (0.141, 1.368)	0.01612	0.895 (0.280, 1.511)	0.00444
				0.623 (-0.263, 1.509)
≥30	0.848	0.04514	0.971	0.02677
				0.944 0.12598

	(0.019, 1.678)	(0.113, 1.829)	(-0.263, 2.152)
P for trend	0.01422	0.00619	0.09121

Outcome was FT3/FT4×100 (continuous). Exposure was serum 25-hydroxyvitamin D [25(OH)D], modeled as a continuous variable and as clinical categories (<20, 20-30, and ≥30 ng/mL; <20 ng/mL as the reference). β represents the difference in FT3/FT4×100 associated with each category (vs <20 ng/mL) or per 1 ng/mL higher 25(OH)D, as appropriate. Model 1 was unadjusted; Model 2 was adjusted for age and sex; Model 3 was additionally adjusted for BMI, SBP, DBP, HbA1c (Box-Cox), TC (Box-Cox), HDL-C (Box-Cox), LDL-C, TG (Box-Cox), eGFR (Box-Cox), UA (Box-Cox), AST (Box-Cox), ALT (Box-Cox), CRP (Box-Cox), WBC (Box-Cox), VFA (Box-Cox), SFA (Box-Cox), current smoking, and current drinking. Analyses used a complete-case approach; model-specific sample sizes are shown in column headers and may differ due to missing covariates. P for trend was calculated by modeling the ordered 25(OH)D categories as an ordinal term in each model. Estimates are reported as β (95% CI) with two-sided P values. 25(OH)D: 25-hydroxyvitamin D.

Supplementary Table 3 Associations between serum 25-hydroxyvitamin D and the FT3/FT4 ratio across three extended multivariable linear regression models (models 3a-3c)

Exposure	Model 3a β (95% CI)	P value	Model 3b β (95% CI)	P value	Model 3c β (95% CI)	P value
25(OH)D	0.075 (0.023, 0.126)	0.0047	0.072 (0.025, 0.119)	0.0028	0.050 (0.007, 0.092)	0.0214
25(OH)D						

quartile						
Q1	reference		reference		reference	
Q2	1.218	0.0332	1.267	0.0198	1.006	0.0362
	(0.100,		(0.204,		(0.066,	
	2.336)		2.331)		1.947)	
Q3	1.774	0.0040	1.309	0.0235	1.140	0.0210
	(0.570,		(0.173,		(0.174,	
	2.978)		2.444)		2.106)	
Q4	1.180	0.0539	1.112	0.0504	0.766	0.1279
	(-0.017,		(0.000,		(-0.219,	
	2.377)		2.223)		1.750)	
P for trend	0.0498		0.0887		0.1456	

Values are linear regression coefficients (β) with 95% confidence intervals (CIs) for the association between serum 25(OH)D and the FT3/FT4 ratio (modelled as FT3/FT4 \times 100 for scaling, if applicable). Quartiles of 25(OH)D were analysed with the lowest quartile (Q1) as the reference; P for trend was calculated by modelling quartile categories as an ordinal continuous variable. Model 3a (adiposity-extended model) adjusted for sex, age, BMI, diastolic blood pressure (DBP), systolic blood pressure (SBP), LDL-C, HbA1c, total cholesterol (TC), HDL-C, AST, ALT, eGFR, smoking, drinking, visceral fat (VF), and subcutaneous fat (SF). Model 3b (inflammation-extended model) adjusted for sex, age, DBP, SBP, LDL-C, HbA1c, TC, HDL-C, AST, ALT, triglycerides (TG), uric acid (UA), eGFR, C-reactive protein (CRP), white blood cell count (WBC), smoking, and drinking. Model 3c (parsimonious model) adjusted for sex, age, DBP, SBP, AST, ALT, eGFR, smoking, and drinking. All models were fitted using complete-case analysis; the total sample size was N=1271. 25(OH)D: 25-hydroxyvitamin D.

Supplementary Table 4 Comparison of participants included in the fully

adjusted model (complete-case) versus those excluded due to missing covariates (*n* = 1271 with available 25(OH)D)

Characteristic	Non-complete-case (n=694)	Complete-case (n=577)	Standardized diff.	<i>P</i> value
Age (years)	53.22 ± 13.34	55.64 ± 11.57	0.19	0.004
Sex (%)			0.08	0.146
Female	279 (40.20%)	209 (36.22%)		
Male	415 (59.80%)	368 (63.78%)		
Current drinking, n (%)			0.00	0.985
No	436 (62.82%)	404 (70.02%)		
Yes	206 (29.68%)	173 (29.98%)		
Missing	52 (7.49%)	0		
Current smoking, n (%)			0.03	0.631
No	443 (63.83%)	402 (69.67%)		
Yes	200 (28.82%)	175 (30.33%)		
Missing	51 (7.35%)	0		
DBP (mmHg)	74.80 ± 9.26	76.00 ± 8.81	0.13	0.008
SBP (mmHg)	126.01 ± 13.80	128.14 ± 13.56	0.16	0.007
LDL-C (mmol/L)	2.82 ± 0.99	2.72 ± 0.98	0.11	0.076
eGFR (mL/min/1.73 m ²)	104.66 ± 15.77	101.95 ± 14.45	0.18	0.016
BMI (kg/m ²)	25.28 ± 4.20	25.42 ± 3.35	0.04	0.076
25(OH)D	22.40 ± 8.44	22.90 ± 7.94	0.06	0.176

(ng/ml)				
CRP (mg/L)	1.92 (0.90-4.39)	1.44 (0.68-3.08)	0.14	<0.001
FT3/FT4*100	31.12 ± 5.04	32.14 ± 5.18	0.20	<0.001
VFA (cm ²)	96.00 (70.00-121.25)	91.00 (70.00-114.00)	0.10	0.113
SFA (cm ²)	168.00 (130.00-223.00)	163.00 (129.00-201.00)	0.19	0.019

All participants included in this table had available 25(OH)D measurements (N = 1,271). The complete-case group (n = 577) comprised participants with non-missing data for all covariates in the fully adjusted model (Model 3), whereas the non-complete-case group (n = 694) included participants excluded from Model 3 due to missing covariates. Values are presented as mean ± SD for approximately normally distributed variables, median (Q1–Q3) for skewed variables, and n (%) for categorical variables. Missing categories for current smoking and current drinking are shown explicitly. Standardized differences quantify between-group imbalance (absolute values closer to 0 indicate better balance). P values are descriptive (two-sample t test or Wilcoxon rank-sum test for continuous variables, and χ^2 test or Fisher’s exact test for categorical variables) and were not adjusted for multiple comparisons. DBP: Diastolic blood pressure; SBP: Systolic blood pressure; LDL-C: Low-density lipoprotein cholesterol; eGFR: Estimated glomerular filtration rate; BMI: Body mass index; VFA: Visceral fat area; SFA: Subcutaneous fat area; 25(OH)D: 25-hydroxyvitamin D.

Supplementary Table 5 Variance inflation factors for predictors included in the fully adjusted linear regression model (model 3)

Predictor	VIF
TC	8.25
LDL-C	4.93

Age	3.77
ALT	3.75
eGFR	3.46
AST	3.42
BMI	3.34
SFA	3.21
TG	2.98
VFA	2.49
HDL-C	2.45
Sex (male <i>vs</i> female)	1.77
DBP	1.76
SBP	1.74
UA	1.59
CRP	1.32
Current drinking (yes <i>vs</i> no)	1.31
HbA1C	1.21
WBC	1.20
25(OH)D	1.17
Current smoking (yes <i>vs</i> no)	1.17

Variance inflation factors (VIFs) were calculated to assess multicollinearity among predictors included in the fully adjusted multivariable linear regression model (Model 3). Continuous variables were entered as the same transformed terms used in the primary analysis (Box-Cox transformation applied where specified). Categorical variables were coded as indicator terms; the reference categories were Female for sex and No for current smoking and current drinking. Larger VIF values indicate greater collinearity; values <5 are commonly considered to reflect low-to-moderate collinearity, whereas values ≥ 10 suggest substantial multicollinearity. VIF: Variance inflation factor; TC: Total cholesterol; LDL-C: Low-density lipoprotein cholesterol; ALT: Alanine

aminotransferase; eGFR: Estimated glomerular filtration rate; AST: Aspartate aminotransferase; BMI: Body mass index; TG: Triglycerides; VFA: Visceral fat area; SFA: Subcutaneous fat area; HDL-C: High-density lipoprotein cholesterol; DBP: Diastolic blood pressure; SBP: Systolic blood pressure; UA: Uric acid; CRP: C-reactive protein; HbA1C: Glycated hemoglobin; WBC: White blood cell count; 25(OH)D: 25-hydroxyvitamin D.

Supplementary Table 6 Sensitivity analysis using multiple imputation: association between 25(OH)D and FT3/FT4 × 100 in the fully adjusted model (complete-case *vs* MI pooled)

Exposure	Complete-case β (95% CI)	<i>P</i> value	MI pooled β (95% CI)	<i>P</i> value
25(OH)D	0.088 0.139)	(0.037, <0.001	0.062 0.101)	(0.024, 0.002
25(OH)D quartile				
Q1	reference		reference	
Q2	0.846 1.943)	(-0.251, 0.131	0.663 1.480)	(-0.153, 0.111
Q3	1.517 2.671)	(0.362, 0.010	1.052 1.904)	(0.200, 0.016
Q4	1.246 2.419)	(0.074, 0.0378	0.873 1.742)	(0.005, 0.049
<i>P</i> for trend	0.024		0.034	

Values are regression coefficients (β) with 95% confidence intervals (CIs) from multivariable linear regression models with FT3/FT4×100 as the outcome. Analyses were restricted to participants with available 25(OH)D measurements (n = 1,271). Complete-case estimates were obtained from the

fully adjusted model using participants with complete covariate data (n = 577). For the sensitivity analysis, missing covariates were handled using multiple imputation (m = 30 imputations), and results were pooled according to Rubin's rules. The fully adjusted model (Model 3) included age, sex, BMI, SBP, DBP, HbA1c, TC, HDL-C, LDL-C, TG, eGFR, UA, AST, ALT, CRP, WBC, VFA, SFA, current smoking, and current drinking. Box-Cox transformations were applied to HbA1c, TC, HDL-C, TG, eGFR, UA, AST, ALT, CRP, WBC, VFA, and SFA as previously described. Quartiles of 25(OH)D were defined using cut-points derived from the original dataset (.imp = 0), with Q1 as the reference category. P for trend was calculated by modeling the quartile variable as an ordinal term (1-4). 25(OH)D: 25-hydroxyvitamin D.