frontiers in Surgery

TYPE Original Research
PUBLISHED 02 November 2026
DOI 10.3389/fsurg.2026.1892362

Check for updates

OPEN ACCESS

EDITED BY
Gabriel Sandblom,
Karolinska Institutet (KI), Sweden

REVIEWED BY
Inyoung Lee,
Korea University Medical Center, Republic of Korea
Emre Teke,
University of Health Sciences, Türkiye
Yuxiu Pu,
The Second Affiliated Hospital of Kunming Medical University, China

*CORRESPONDENCE
Güney Özkaya
guneyozkaya4@outlook.com;
guney.ozkaya@saglik.gov.tr

RECEIVED 27 May 2026
REVISED 14 October 2026
ACCEPTED 14 October 2026
PUBLISHED 02 November 2026

CITATION
Özkaya G, Abdullah S, Yazıcı O, Gündoğdu A and Öztütüncü KÖ (2026) Thyroid hormone changes and their associations with weight loss after laparoscopic sleeve gastrectomy: a 12-month cohort study.
Front. Surg. 13:1892362.
doi: 10.3389/fsurg.2026.1892362

COPYRIGHT
© 2026 Özkaya, Abdullah, Yazıcı, Gündoğdu and Öztütüncü. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

Thyroid hormone changes and their associations with weight loss after laparoscopic sleeve gastrectomy: a 12-month cohort study

Güney Özkaya[1]*, Sangar Abdullah[1], Oğuzhan Yazıcı[1], Adnan Gündoğdu[1] and Kubilay Özgür Öztütüncü[2]

[1]Department of General Surgery, Sancaktepe Şehit Prof. Dr. İlhan Varank Training and Research Hospital, Istanbul, Türkiye, [2]Department of General Surgery, Kanuni Sultan Suleiman Training and Research Hospital, Istanbul, Türkiye

Introduction: In patients with obesity, thyroid-stimulating hormone (TSH) and free triiodothyronine (fT3) concentrations and the ratio of fT3 to free thyroxine (fT4) are often higher than in normal-weight individuals. Although laparoscopic sleeve gastrectomy (LSG) alters thyroid function, the temporal trajectory of these changes and the factors associated with them remain incompletely characterized. We therefore examined, in 232 patients followed for 12 months after LSG, how thyroid hormone parameters changed over the first postoperative year and which clinical and iron-related factors were associated with these changes.
Methods: In this retrospective cohort, patients (including 25 with treated autoimmune hypothyroidism) were assessed before surgery and at 6 and 12 months, with thyroid hormone trajectories analyzed by repeated-measures testing and their correlates examined by multivariable regression.
Results: TSH, fT3, and the calculated fT3/fT4 ratio decreased significantly over 12 months while fT4 rose modestly; changes were evident at 6 months, with no statistically significant additional change detected between 6 and 12 months (TSH, p = 0.482). No statistically significant association was detected between the changes in TSH, fT3, and fT4 and weight-loss magnitude within the observed range of total weight loss (11.0%–48.3%), including in the 207 patients not receiving levothyroxine; in the adjusted model for the TSH change, a 10-percentage-point difference in total weight loss corresponded to −0.03 μIU/mL (95% CI −0.15 to +0.09). No statistically significant association was detected with the changes in inflammatory markers. Each change was most strongly associated with its own baseline value, but these associations partly reflect mathematical coupling, measurement error, and regression to the mean and are not interpreted as physiological effects. A weak, nominal association between the changes in TSH and ferritin was specification-dependent and is regarded as exploratory. Among levothyroxine-treated patients, the dose was reduced in 16 of 25 (64%; 95% CI 44.5–79.8), a descriptive observation that cannot be attributed to surgery alone.
Discussion: Within the observed range, these data do not show a detectable association between weight-loss magnitude and thyroid hormone changes after LSG, although they do not establish equivalence; the exploratory ferritin signal warrants confirmation in prospective studies with comprehensive iron indices.

KEYWORDS
ferritin, fT3/fT4 ratio, hypothyroidism, laparoscopic sleeve gastrectomy, levothyroxine, thyroid function, weight loss

1 Introduction

Obesity has reached pandemic proportions globally, with a pooled analysis of over 3,600 population-representative studies estimating that more than one billion people are currently living with obesity worldwide—a prevalence more than double that recorded in 1990 (1). Obesity is a state of chronic low-grade inflammation, driven by the dysregulated secretion of pro-inflammatory adipokines—including leptin, tumor necrosis factor-α, and interleukin-6—from hypertrophied adipose tissue (2). This inflammatory milieu influences the hypothalamic-pituitary-thyroid (HPT) axis: individuals with obesity have higher serum TSH and fT3 concentrations than normal-weight counterparts, with adiposity-related leptin excess, altered deiodinase activity, and reduced TSH receptor expression in adipose tissue proposed as contributing mechanisms, and an elevated fT3/fT4 ratio has been reported in cohorts of patients with obesity (3, 4). The pooled prevalence of subclinical hypothyroidism in patients with obesity has been estimated at 14.6% (95% CI: 9.2–20.9), a rate substantially exceeding that observed in populations without obesity, and the coexistence of these two conditions creates a clinically complex metabolic profile (5). Furthermore, inflammatory adipokines may independently compromise deiodinase function and alter peripheral T4-to-T3 conversion, suggesting a bidirectional interaction between adiposity-driven inflammation and thyroid hormone homeostasis (6).

Laparoscopic sleeve gastrectomy (LSG) has emerged as the most widely performed bariatric procedure worldwide, accounting for 58.2% of all bariatric surgical procedures in the most recent IFSO global survey (7). Surgery-induced weight loss through LSG is consistently associated with reductions in TSH and fT3 alongside improvements in metabolic parameters (8–10). A meta-analysis of bariatric surgery outcomes further confirmed that surgery is associated with resolution of subclinical hypothyroidism and reduced levothyroxine (LT4) requirements in hypothyroid patients (11). That the overall trajectory of TSH and fT3 declines after LSG is therefore well established. Less well characterized, however, are several questions that this cohort was designed to address: whether the magnitude of these thyroid changes depends on how much weight is lost; how the fT3/fT4 ratio, a calculated serum index, behaves relative to its individual components; and whether the concurrent decline in inflammatory markers, indexed by the neutrophil-to-lymphocyte ratio (NLR), platelet-to-lymphocyte ratio (PLR), and C-reactive protein (CRP), tracks with thyroid changes—a question previously examined with cytokine and CRP measurements in a smaller LSG cohort (12). A further dimension is iron status: iron is a cofactor for thyroid peroxidase, the key enzyme in thyroid hormone synthesis (13), and bariatric surgery frequently leads to iron deficiency through reduced intake and impaired absorption (14). Changes in serum iron have been related to changes in fT4 in a small LSG cohort followed for 6 months (15), but whether postoperative changes in ferritin are associated with thyroid changes over 12 months, after adjustment for weight loss and inflammatory markers, is less well characterized.

Against this background, the present study addressed two questions in a cohort of 232 patients followed for 12 months after LSG: first, how thyroid hormone parameters (TSH, fT3, fT4, and the fT3/fT4 ratio) changed over the first postoperative year; and second, which clinical and iron-related factors were associated with these changes. Rather than re-establishing the now well-documented directional trajectory, the analysis focuses on these less-resolved questions—in particular, whether the thyroid changes were associated with weight-loss magnitude and with concurrent changes in inflammatory markers, and whether an iron-related signal is present. LT4 dose changes in the treated hypothyroid subgroup were analyzed descriptively.

2 Materials and methods

2.1 Study design and patient population

This was a single-center, retrospective cohort study based on routinely maintained electronic medical records. All consecutive adult patients (age ≥18 years) who underwent laparoscopic sleeve gastrectomy (LSG) at Sancaktepe Şehit Prof. Dr. İlhan Varank Training and Research Hospital, Istanbul, Turkey, between January 2022 and April 2025 and who attended the scheduled 12-month follow-up visit were considered for inclusion. During this period, 263 patients underwent LSG and were scheduled for 12-month follow-up; 251 (95.4%) attended the 12-month visit, whereas 12 (4.6%) did not attend any postoperative follow-up visit. Thyroid function tests and the clinical data required to assess eligibility were not available for these 12 patients; therefore, their eligibility could not be assessed and they could not be compared with the analytic cohort. The study was conducted in accordance with the Declaration of Helsinki and received retrospective approval from the Institutional Review Board (Decision No. 2026/255). Given the retrospective design and the use of de-identified clinical data, the requirement for individual informed consent was waived by the ethics committee.

Inclusion criteria were: body mass index (BMI) ≥35 kg/m^2 and age 18–65 years. Patients were excluded if they had a history of thyroid surgery, radioactive iodine therapy, or known structural or functional thyroid disease other than autoimmune hypothyroidism, or incomplete laboratory data, defined as missing thyroid function tests (TSH, fT3, or fT4) at any of the three timepoints (preoperative, 6 months, and 12 months). Patients with pre-existing autoimmune hypothyroidism receiving levothyroxine (LT4) replacement therapy were not excluded and were stratified as an analytic subgroup.

Of 251 patients who attended the 12-month visit, 16 were excluded for thyroid-related eligibility criteria (9 with a history of thyroid surgery, 4 with previous radioactive iodine therapy,

Abbreviations

BMI, body mass index; CRP, C-reactive protein; DM, diabetes mellitus; EWL, percentage excess weight loss; fT3, free triiodothyronine; fT4, free thyroxine; HPT, hypothalamic-pituitary-thyroid axis; HT, hypertension; IQR, interquartile range; LDL, low-density lipoprotein; LSG, laparoscopic sleeve gastrectomy; LT4, levothyroxine; NLR, neutrophil-to-lymphocyte ratio; PLR, platelet-to-lymphocyte ratio; TPO, thyroid peroxidase; TSH, thyroid-stimulating hormone; TWL, percentage total weight loss; ΔFerritin, change in serum ferritin; ΔfT3, change in fT3; ΔfT4, change in fT4; ΔTSH, change in TSH.

and 3 with known structural or functional thyroid disease other than autoimmune hypothyroidism), and 3 otherwise eligible patients were excluded because of incomplete laboratory data at the 6- or 12-month visit (missing variables are specified in Supplementary Table S8). The remaining 232 patients met all inclusion criteria and constituted the final analytic cohort (Supplementary Figure S3). Baseline characteristics of the included cohort, the 16 patients excluded for thyroid-related criteria, and the 3 patients excluded for incomplete laboratory data are presented in Supplementary Table S8. Data collection was completed in May 2026, ensuring that all included patients had a minimum of 12 months of postoperative follow-up prior to analysis.

2.2 Surgical technique

All LSG procedures were performed by experienced metabolic and bariatric surgeons within the same surgical team, ensuring standardized perioperative management and technical uniformity. Gastric resection was performed along the greater curvature beginning 4–6 cm proximal to the pylorus and extending to the angle of His, using a 38-Fr bougie for calibration. The extracted gastric specimen was sent for histopathological examination. Antithrombotic prophylaxis and perioperative care followed institutional protocols consistent with enhanced recovery after surgery (ERAS) principles.

2.3 Data collection and laboratory measurements

Demographic and clinical data, including age, sex, and BMI, were retrieved from electronic medical records to characterize the cohort (Table 1). Type 2 diabetes mellitus (DM) and hypertension (HT) were additionally analyzed as covariates in the multivariable models.

Thyroid function tests—serum thyroid-stimulating hormone (TSH), free triiodothyronine (fT3), and free thyroxine (fT4)—were obtained as part of the standard preoperative workup and repeated at scheduled postoperative visits at 6 and 12 months; the allowed window was ±1 month around each scheduled visit (5–7 and 11–13 months after surgery, respectively), and all included patients were assessed within these windows. Thyroid function tests and ferritin were measured by electrochemiluminescence immunoassay on a cobas e 801 module, and C-reactive protein (CRP) by an immunoturbidimetric assay (Tina-quant C-Reactive Protein IV; measuring range 0.6–350 mg/L) on a cobas c 702 module of a cobas 8000 analyzer (Roche Diagnostics); the same assays were used throughout the study period. The manufacturer's reference ranges were used (TSH 0.27–4.2 μIU/mL; fT3 2.0–4.4 pg/mL; fT4 0.92–1.68 ng/dL; ferritin 30–400 ng/mL in men and 13–150 ng/mL in women). The fT3/fT4 ratio (fT3 in pg/mL divided by fT4 in ng/dL) was computed at each timepoint and is reported as a calculated serum index. It is not a direct measure of peripheral T4-to-T3 conversion, and no laboratory reference range is available for it; because fT3 and fT4 are expressed in different units, its absolute value should not be compared across studies using different assays or units.

Inflammatory markers—neutrophil-to-lymphocyte ratio (NLR), platelet-to-lymphocyte ratio (PLR), and CRP—were tracked across timepoints as indices of systemic inflammation; NLR and PLR were derived from automated complete blood count differentials. The changes in NLR and CRP were analyzed as covariates in the regression models. Serum ferritin was measured on the cobas e 801 module, and its 12-month change (ΔFerritin) was analyzed as an iron-related covariate, alongside the change in low-density lipoprotein cholesterol (LDL) as a metabolic covariate. Because ferritin is also an acute-phase reactant, it was not used to define iron deficiency or to estimate its prevalence. Hemoglobin, serum iron, and transferrin saturation were not included in the extracted dataset and were therefore not analyzed.

Weight-loss outcomes were assessed as percentage excess weight loss (%EWL), percentage total weight loss (%TWL), and BMI at 6 and 12 months. Body weight was recorded at each postoperative visit and combined with baseline height to calculate BMI. Consistent with the American Society for Metabolic and Bariatric Surgery reporting standards (16), %TWL was calculated as (preoperative weight − follow-up weight)/preoperative weight × 100, and %EWL as (preoperative weight − follow-up weight)/(preoperative weight − ideal body weight) × 100, with ideal body weight defined as the weight corresponding to a BMI of 25 kg/m^2. Because %EWL depends on the definition of ideal body weight, values are not directly comparable with cohorts using a different denominator; %TWL, which does not depend on an ideal-weight definition, was therefore analyzed in parallel. For each repeated-measures variable, the absolute change from baseline to 12 months (calculated as the 12-month value minus the preoperative value; e.g., ΔTSH, ΔFerritin, ΔBMI) was derived for use in the correlation and regression analyses.

2.4 Hypothyroid subgroup

Patients with a known preoperative diagnosis of autoimmune hypothyroidism receiving LT4 replacement therapy were stratified as an analytic subgroup ($n = 25$), as this population may demonstrate distinct thyroid adaptation patterns following bariatric surgery-induced weight loss. LT4 doses (mcg/day) at each timepoint were recorded, and any change in dose relative to the preoperative value was categorized as decreased, unchanged, or increased. This subgroup was analyzed separately to describe levothyroxine dose dynamics and to examine whether its thyroid hormone trajectories paralleled those of the 207 untreated euthyroid patients. LT4 dose adjustments were made at the discretion of the operating surgeon based on postoperative thyroid function test results, without formal endocrinology referral, reflecting routine clinical practice at our institution. Thyroid control was described as the number of patients with TSH and fT4 within the laboratory reference ranges at each timepoint, and, for patients whose dose changed, the timing of the first change (by 6 months or between 6 and 12 months) was recorded (Table 5). Because dosing was therefore guided by thyroid test results, this subgroup analysis is descriptive and does not support the inference that surgery alone caused the observed dose changes.

TABLE 1 Baseline demographic and clinical characteristics of the study cohort ($n = 232$).

Characteristic	Overall ($n = 232$)	Euthyroid ($n = 207$)	LT4-treated ($n = 25$)	p-value
Demographics				
Age (years), mean ± SD	37.9 ± 9.9	37.2 ± 9.3	43.4 ± 12.7	**0.020***
Sex, Female, n (%)	182 (78.4%)	159 (76.8%)	23 (92.0%)	0.120†
BMI (kg/m^2)	43.7 [41.2–47.0]	43.8 [41.2–47.0]	42.9 [41.1–47.2]	0.898
Comorbidities				
Diabetes mellitus, n (%)	52 (22.4%)	47 (22.7%)	5 (20.0%)	0.958
Hypertension, n (%)	63 (27.2%)	55 (26.6%)	8 (32.0%)	0.735
Weight loss outcomes				
%EWL at 6 months	62.5 [53.8–73.9]	62.4 [53.8–73.8]	64.6 [54.6–74.3]	0.965
%EWL at 12 months	76.4 [63.3–88.4]	76.1 [63.3–88.5]	79.8 [65.2–87.4]	0.561
%TWL at 6 months	27.1 [23.5–31.0]	27.6 [23.5–31.0]	25.9 [23.5–29.0]	0.506
%TWL at 12 months	32.2 [27.6–37.1]	32.3 [27.8–37.3]	31.4 [27.2–34.5]	0.512
BMI at 6 months (kg/m^2)	31.9 [29.5–34.8]	32.1 [29.5–34.7]	31.5 [29.3–35.9]	0.811
BMI at 12 months (kg/m^2)	29.7 [27.1–32.8]	29.7 [27.1–32.8]	29.2 [26.9–33.3]	1.000
Baseline thyroid function				
TSH (μIU/mL)	1.96 [1.52–2.55]	1.91 [1.48–2.46]	2.67 [1.87–3.88]	**0.005***
fT3 (pg/mL)	3.30 [3.03–3.59]	3.33 [3.05–3.61]	3.14 [2.94–3.24]	**0.008***
fT4 (ng/dL)	1.17 [1.07–1.28]	1.17 [1.06–1.28]	1.21 [1.07–1.28]	0.669
Baseline inflammatory markers				
NLR	2.24 [1.77–2.91]	2.24 [1.82–2.92]	2.29 [1.68–2.78]	0.427
PLR	114.8 [94.7–147.6]	115.1 [95.6–146.6]	110.1 [84.7–155.4]	0.487
CRP (mg/L)	7.24 [3.63–15.53]	7.24 [3.71–15.20]	6.85 [3.56–15.50]	0.887
Baseline metabolic parameters				
LDL (mg/dL)	108.0 [89.0–135.1]	108.0 [88.0–137.3]	108.0 [99.5–134.0]	0.649
Ferritin (ng/mL)	49.4 [23.0–86.6]	49.0 [22.0–88.0]	53.7 [28.4–82.2]	0.942

Continuous variables are presented as mean ± SD or median [IQR] based on distribution. Categorical variables are presented as n (%). Bold values indicate $p < 0.05$. LDL was available for 231 patients (one value recorded as >400 mg/dL). BMI, body mass index; %EWL, percentage excess weight loss; %TWL, percentage total weight loss; TSH, thyroid-stimulating hormone; fT3, free triiodothyronine; fT4, free thyroxine; NLR, neutrophil-to-lymphocyte ratio; PLR, platelet-to-lymphocyte ratio; CRP, C-reactive protein; LDL, low-density lipoprotein; LT4, levothyroxine; IQR, interquartile range.

*$p < 0.05$.

†Between-group comparisons were performed using the Mann–Whitney U test for continuous variables and the chi-square or Fisher's exact test (†) for categorical variables.

2.5 Statistical analysis

Analyses were performed in Python 3.11 (SciPy, statsmodels, pandas, NumPy). Normality was assessed with the Shapiro–Wilk test; inflammatory markers and preoperative TSH and fT4 departed from normality ($p < 0.001$), whereas preoperative fT3 did not. Rank-based tests were therefore used for all repeated-measures comparisons and for between-group comparisons of continuous variables, and the same approach was applied to all related outcomes for consistency of interpretation. A two-tailed $p < 0.05$ was considered statistically significant unless otherwise specified. Displayed p values are unadjusted unless labelled otherwise; the multiplicity strategy for each analysis is described below.

To address the first question—how thyroid hormone parameters changed over time—the Friedman test was used across the three timepoints, followed by pairwise Wilcoxon signed-rank tests (normal approximation without continuity correction; tied absolute differences were assigned average ranks with the corresponding variance correction, and pairs with a zero difference were excluded from the calculation of Z), with significance assessed against a Bonferroni-corrected threshold of $\alpha = 0.017$ for the three pairwise comparisons; displayed pairwise p values are unadjusted. Effect sizes were reported as $r = Z/\sqrt{n}$, where n is the total number of pairs. For each interval, the paired change was estimated with the Hodges–Lehmann estimator, defined as the median of all pairwise averages of the individual differences (pseudomedian), with a 95% confidence interval obtained by the Wilcoxon signed-rank/Walsh-average method; this estimand differs from both the difference between the medians at two timepoints and the median of the individual changes. The signed-rank test assesses whether the paired differences are distributed symmetrically about zero rather than whether the marginal medians are equal. The same procedures

were applied to the inflammatory markers (Supplementary Table S1). Because measurements were available only preoperatively and at 6 and 12 months, the timing of changes within the first 6 months could not be determined. As a descriptive measure of TSH burden, the proportion of patients with TSH >2.5 μIU/mL, a non-standard cut-off, was compared across timepoints by the Cochran *Q* test with McNemar pairwise comparisons, and paired preoperative-to-12-month transitions above 2.5 μIU/mL and above the upper reference limit (4.2 μIU/mL) were tabulated (Supplementary Table S10).

To address the second question—which factors were associated with the thyroid hormone changes—Spearman correlations, with 95% confidence intervals obtained by Fisher *z* transformation, were computed between the 12-month thyroid changes and the corresponding clinical, metabolic, iron-related, and inflammatory changes using all available pairs, with Benjamini–Hochberg false discovery rate correction across all correlations in Table 3. Associations were then examined by multivariable ordinary least-squares regression. The principal outcome was ΔTSH and the principal exposure was weight-loss magnitude at 12 months; ΔfT3 and ΔfT4 were secondary outcomes. Six models were fitted, one for each outcome with either %EWL (Model A) or %TWL (Model B) as the weight-loss metric, each adjusted for the same prespecified covariates (age, sex, DM, HT, hypothyroidism status, baseline TSH, baseline fT3, baseline fT4, ΔLDL, ΔCRP, ΔFerritin, and ΔNLR); all estimates are reported in Supplementary Table S7 and selected estimates in Table 4. Coefficients are expressed per unit of each covariate (per percentage point for %EWL and %TWL), in μIU/mL for ΔTSH, pg/mL for ΔfT3, and ng/dL for ΔfT4. No multiplicity correction was applied across the six models or their covariates; regression *p* values are therefore nominal. The associations of hypothyroidism status and ΔFerritin were treated as exploratory, and the baseline coefficients were interpreted in light of mathematical coupling (see below). 95% confidence intervals were obtained by nonparametric patient-level bootstrap resampling (2,000 resamples; percentile intervals), and all resampled models were estimable. Because parametric *p* values and bootstrap intervals derive from different inferential procedures, they may disagree for borderline estimates; such estimates were not interpreted as robust. Model diagnostics comprised examination of the residual distribution, the Breusch–Pagan test for heteroscedasticity, the Ramsey RESET test for functional form, variance inflation factors, and Cook's distance (>4/*n*); coefficients of interest were additionally re-estimated with heteroscedasticity-consistent (HC3) standard errors and after exclusion of influential observations (Supplementary Table S11). Baseline LDL in one patient was reported by the laboratory as ">400 mg/dL", a censored, nonnumeric result whose exact value was unknown; this patient was therefore excluded from the multivariable models ($n = 231$) but retained in all descriptive analyses ($n = 232$), and the models were refitted without ΔLDL to include all 232 patients as a sensitivity analysis (Supplementary Table S11, Panel C). The only other missing values concerned glycated hemoglobin (HbA1c) (up to 3 patients), and analyses involving HbA1c used all available pairs.

Within the levothyroxine-treated subgroup, LT4 dose changes across timepoints were evaluated by the Friedman test, the proportions of patients whose dose decreased, remained unchanged, or increased were reported with Wilson 95% confidence intervals, and baseline LT4 dose and weight loss were compared between patients with and without dose reduction by the Mann–Whitney *U* test (Supplementary Table S5). Within-subgroup paired changes in thyroid hormones were estimated as described above, and differences in 12-month change between the hypothyroid and euthyroid groups were estimated as Hodges–Lehmann shifts with Mann–Whitney-based 95% confidence intervals (Supplementary Table S2). Given the small subgroup size, results are presented as estimates with confidence intervals rather than interpreted on the basis of *post hoc* power.

Because a change score is mathematically coupled to its own baseline value, the baseline coefficients in the change-score models were not interpreted as estimates of a physiological effect. Two complementary analyses are reported (Supplementary Table S6). First, Oldham's method (Pearson correlation between each patient's mean of the preoperative and 12-month values and the corresponding change) was reported alongside the conventional baseline–change correlation; it addresses a different association from the regression coefficient and does not estimate a baseline-independent physiological component or the contribution of regression to the mean. Second, the ΔTSH model (Model A) was refitted as an analysis of covariance (ANCOVA), with the 12-month TSH value as the dependent variable and baseline TSH as a covariate, using the same 231 patients, covariates, and estimation procedure. For ordinary least squares, this is an exact reparameterization of the change-score model: the baseline coefficient differs by exactly 1, whereas all other coefficients and the residuals are identical, so the difference in R^2 reflects the different outcome variance rather than a correction for coupling. These analyses do not separate the contributions of mathematical coupling, measurement error, and regression to the mean.

The robustness of the principal findings was further examined in (i) analyses restricted to the 207 untreated euthyroid patients, repeating the trajectory, correlation, and regression analyses (Supplementary Table S9); (ii) analyses excluding patients with preoperative TSH above 4.0 μIU/mL, a pragmatic cut-off slightly below the laboratory upper reference limit, and, for comparison, above the upper reference limit itself (4.2 μIU/mL); these removed 12 and 11 patients, respectively, 5 of whom were receiving LT4 in each case, and are therefore not equivalent to excluding LT4-treated patients; TSH above these cut-offs alone does not establish subclinical hypothyroidism (Supplementary Table S3); (iii) subgroup analyses by comorbidity, sex, and BMI class with Benjamini–Hochberg correction (Supplementary Table S4); and (iv) sensitivity analyses of the ΔFerritin coefficient, comprising exclusion of influential observations, winsorization at the 1st and 99th percentiles, additional adjustment for preoperative ferritin, and inclusion of the patient with the censored LDL value (Supplementary Table S10). Analyses added in response to peer review (Supplementary Tables S6, S9–S11, the Hodges–Lehmann estimates, and the description of thyroid control in the LT4 subgroup) were *post hoc*. Statistical code is available from the corresponding author on request.

3 Results

3.1 Baseline characteristics

A total of 232 patients were included (182 women [78.4%]; mean age 37.9 ± 9.9 years; median BMI 43.7 kg/m^2 [IQR 41.2–47.0]). Twenty-five patients (10.8%) had pre-existing autoimmune hypothyroidism and were receiving levothyroxine (LT4) replacement; the remaining 207 (89.2%) were euthyroid. Full baseline demographics, comorbidities, and weight-loss outcomes are presented in Table 1.

As expected, LT4-treated patients differed from euthyroid patients in baseline thyroid status, with higher TSH and lower fT3 (Table 1); baseline thyroid values and hypothyroidism status were included as covariates in the multivariable models. Weight loss at 6 and 12 months did not differ significantly between the two groups (%EWL and %TWL, all $p > 0.05$; Table 1), although similar weight loss does not establish the absence of treatment-related confounding in comparisons of thyroid changes between the groups. For the whole cohort, median %EWL at 12 months was 76.4% and median %TWL was 32.2%, with median BMI declining from 43.7 to 29.7 kg/m^2 (Table 1). At 12 months, %TWL ranged from 11.0% to 48.3%, with 9 patients (3.9%) below 20%, and %EWL ranged from 21.4% to 115.2%, with 19 patients (8.2%) below 50% (Table 3).

3.2 Thyroid hormone changes across timepoints

All four thyroid parameters changed significantly over the three timepoints (Table 2, Figure 1). Changes were evident at 6 months, with no statistically significant additional change detected between 6 and 12 months (TSH, $p = 0.482$; fT3, $p = 0.606$; fT4, $p = 0.360$; fT3/fT4 ratio, $p = 0.714$); for this interval, the 95% confidence intervals of the paired change estimates included zero for all four parameters.

TSH declined from a preoperative median of 1.955 μIU/mL to 1.660 at 6 months and was 1.700 at 12 months; fT3 decreased from 3.300 pg/mL to 2.890 and 2.850 pg/mL; and the fT3/fT4 ratio, a calculated serum index, fell from 2.867 to 2.389 and 2.385. In contrast, fT4 rose modestly, from 1.170 ng/dL to 1.230 and 1.220 ng/dL. Effect sizes for the preoperative-to-12-month change were largest for the fT3/fT4 ratio ($r = 0.77$) and fT3 ($r = 0.75$), followed by TSH ($r = 0.48$) and fT4 ($r = 0.34$). Detailed test statistics, effect sizes, paired change estimates with 95% confidence intervals, and pairwise comparisons are presented in Table 2.

3.3 TSH burden

We additionally examined the proportion of patients with TSH above 2.5 μIU/mL as a descriptive measure of TSH burden. This

TABLE 2 Thyroid hormone changes across three timepoints ($n = 232$).

Variable	Preoperative	6 months	12 months	Friedman χ^2 (p)	Pairwise comparisons (Wilcoxon p/r)	Paired change, Hodges–Lehmann estimate [95% CI]
	Median [IQR]	Median [IQR]	Median [IQR]		Preop–6 months	Preop–6 months
					Preop–12 months	Preop–12 months
					6–12 months	6–12 months
TSH (μIU/mL)	1.955 [1.520–2.552]	1.660 [1.225–2.200]	1.700 [1.270–2.132]	87.72 (<0.001)	<0.001** $r = 0.431$	−0.340 [−0.430, −0.255]
					<0.001** $r = 0.478$	−0.355 [−0.410, −0.290]
					0.482 ns $r = 0.046$	+0.030 [−0.045, +0.105]
fT3 (pg/mL)	3.300 [3.027–3.592]	2.890 [2.640–3.083]	2.850 [2.610–3.140]	225.19 (<0.001)	<0.001** $r = 0.807$	−0.425 [−0.470, −0.385]
					<0.001** $r = 0.749$	−0.455 [−0.495, −0.420]
					0.606 ns $r = 0.034$	−0.015 [−0.055, +0.035]
fT4 (ng/dL)	1.170 [1.068–1.280]	1.230 [1.090–1.320]	1.220 [1.110–1.340]	44.79 (<0.001)	<0.001** $r = 0.276$	+0.035 [+0.020, +0.055]
					<0.001** $r = 0.337$	+0.045 [+0.030, +0.060]
					0.360 ns $r = 0.060$	+0.010 [−0.010, +0.030]
fT3/fT4 Ratio	2.867 [2.570–3.189]	2.389 [2.131–2.675]	2.385 [2.103–2.654]	207.78 (<0.001)	<0.001** $r = 0.753$	−0.468 [−0.523, −0.413]
					<0.001** $r = 0.771$	−0.488 [−0.535, −0.441]
					0.714 ns $r = 0.024$	−0.009 [−0.057, +0.040]

Values expressed as median [IQR]. Friedman test reported as χ^2 statistic with corresponding p-value (df = 2). Wilcoxon signed-rank test with Bonferroni correction ($\alpha = 0.017$) for pairwise comparisons. Displayed p values are unadjusted; significance of pairwise comparisons was assessed against the Bonferroni-corrected threshold. ns, not significant. r, effect size ($r = Z/\sqrt{n}$). The paired change column gives the Hodges–Lehmann estimate of the within-patient paired differences for each interval (follow-up minus earlier timepoint), defined as the median of all pairwise averages of the individual differences (pseudomedian), with its 95% confidence interval (Wilcoxon signed-rank/Walsh-average method; confirmed by bootstrap, $n = 2{,}000$). This estimate differs from the difference between the timepoint medians shown in the first three columns; for near-zero changes the two may differ, including in sign (e.g., fT4 between 6 and 12 months). The fT3/fT4 ratio is a calculated serum index (fT3 in pg/mL divided by fT4 in ng/dL). Confidence intervals are not adjusted for multiple comparisons. TSH, thyroid-stimulating hormone; fT3, free triiodothyronine; fT4, free thyroxine.

**$p < 0.017$ (significant after Bonferroni correction).

10.3389/fsurg.2026.1892362

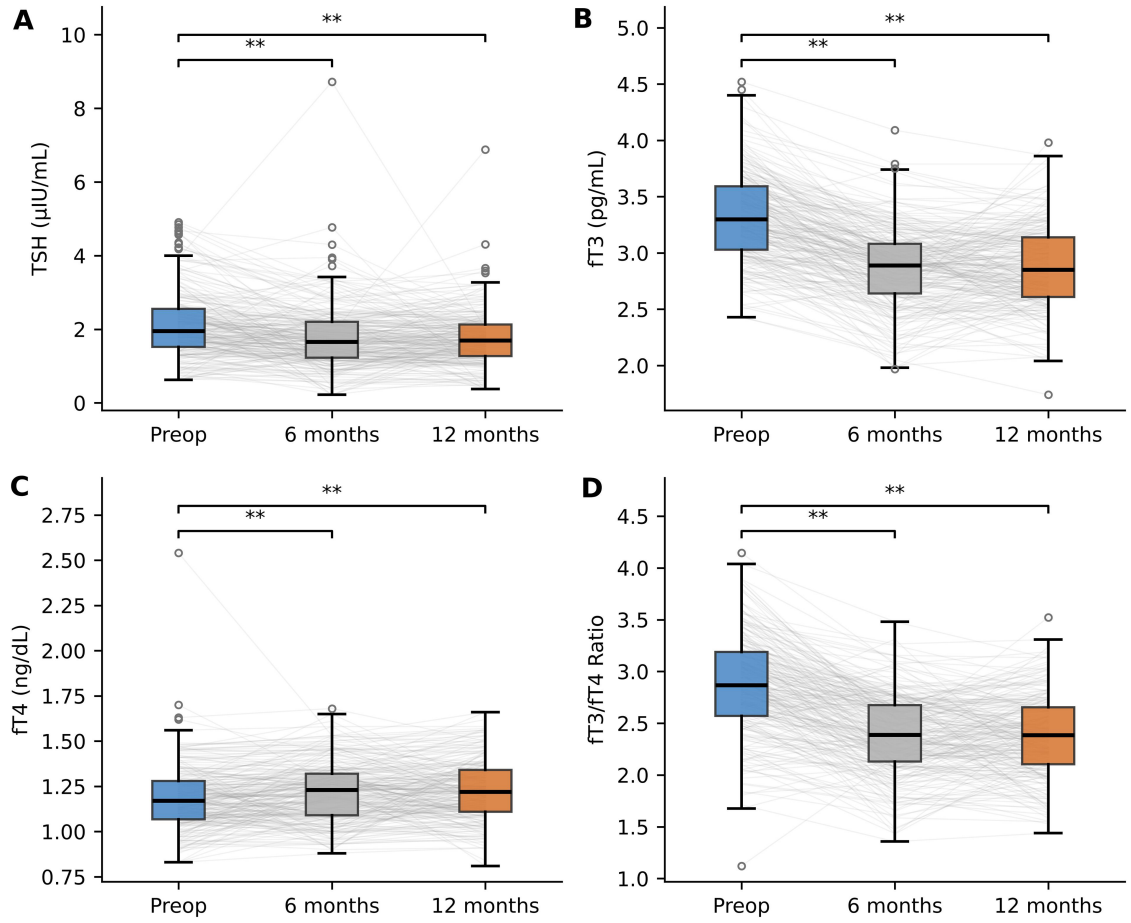


FIGURE 1
Longitudinal changes in thyroid hormone parameters following laparoscopic sleeve gastrectomy ($n = 232$). Box plots show the distribution of **(A)** TSH (µIU/mL), **(B)** fT3 (pg/mL), **(C)** fT4 (ng/dL), and **(D)** fT3/fT4 ratio at preoperative, 6-month, and 12-month timepoints. Horizontal lines within boxes represent medians; box boundaries denote the interquartile range; whiskers extend to 1.5× IQR; circles indicate outliers. Gray lines connect paired observations for each of the 232 patients. Brackets indicate pairwise differences that were statistically significant at the Bonferroni-corrected threshold (Wilcoxon signed-rank test, $\alpha = 0.017$); **raw $p < 0.001$ for all bracketed comparisons. No statistically significant change was detected between 6 and 12 months. TSH, thyroid-stimulating hormone; fT3, free triiodothyronine; fT4, free thyroxine; IQR, interquartile range.

value lies within the laboratory reference range (0.27–4.2 µIU/mL) and is used here as a non-standard, descriptive threshold rather than a diagnostic criterion. This proportion fell from 27.2% (63/232) preoperatively to 12.9% (30/232) at 6 months and 11.2% (26/232) at 12 months (Cochran Q test, $p < 0.001$), with no statistically significant change between 6 and 12 months (McNemar test, $p = 0.607$). Of the 63 patients above 2.5 µIU/mL preoperatively, 46 (73%) were at or below this value at 12 months, whereas 9 of the 169 patients at or below it preoperatively exceeded it at 12 months. Values above the laboratory upper reference limit (4.2 µIU/mL) were uncommon: 11 patients (4.7%) preoperatively, 3 (1.3%) at 6 months, and 2 (0.9%) at 12 months, of whom 5, 2, and 1, respectively, were receiving LT4 (Table 5). Of the 11 patients above this limit preoperatively, 10 were at or below it at 12 months, and 1 patient newly exceeded it at 12 months (Supplementary Table S10).

3.4 Inflammatory marker changes

All three inflammatory markers (NLR, PLR, and CRP) decreased significantly over the 12-month follow-up (all $p < 0.001$; Supplementary Table S1). The largest effect size for the preoperative-to-12-month change was observed for CRP ($r = 0.69$), whose median fell from 7.235 to 2.100 mg/L (paired change −5.750 mg/L [95% CI −7.015, −4.660]), followed by NLR ($r = 0.48$) and PLR ($r = 0.30$). PLR and CRP decreased further between 6 and 12 months ($p = 0.008$ and $p < 0.001$, respectively; both below the Bonferroni-corrected threshold), whereas NLR decreased by 6 months with no statistically significant further change between 6 and 12 months ($p = 0.527$; paired change −0.025 [95% CI −0.105, +0.050]). The changes in these markers were examined in relation to the thyroid hormone changes in the correlation and multivariable analyses (Sections 3.5 and 3.6).

3.5 Correlation between thyroid hormone changes and clinical parameters

Across the 36 correlation pairs, none of the thyroid hormone changes was significantly associated with the concurrent changes in weight loss, metabolic, iron-related, or inflammatory

TABLE 3 Spearman correlation matrix: thyroid hormone changes vs. clinical parameters at 12 months, with 95% confidence intervals.

Thyroid hormone change	%EWL	%TWL	ΔLDL	ΔCRP	ΔHbA1c	ΔALT	ΔFerritin	ΔNLR	ΔPLR
ΔTSH	−0.015 [−0.14, +0.11]	+0.027 [−0.10, +0.16]	−0.027 [−0.16, +0.10]	+0.063 [−0.07, +0.19]	+0.089 [−0.04, +0.22]	+0.089 [−0.04, +0.22]	**−0.138*** [−0.26, −0.01]	+0.103 [−0.03, +0.23]	+0.086 [−0.04, +0.21]
ΔfT3	+0.025 [−0.10, +0.15]	+0.036 [−0.09, +0.16]	−0.078 [−0.21, +0.05]	+0.098 [−0.03, +0.22]	+0.037 [−0.09, +0.17]	+0.069 [−0.06, +0.20]	+0.111 [−0.02, +0.24]	−0.106 [−0.23, +0.02]	+0.012 [−0.12, +0.14]
ΔfT4	−0.018 [−0.15, +0.11]	−0.012 [−0.14, +0.12]	+0.007 [−0.12, +0.14]	+0.095 [−0.03, +0.22]	−0.035 [−0.16, +0.10]	+0.076 [−0.05, +0.20]	−0.001 [−0.13, +0.13]	+0.069 [−0.06, +0.20]	+0.035 [−0.09, +0.16]
Δ(fT3/fT4)	−0.022 [−0.15, +0.11]	−0.015 [−0.14, +0.11]	−0.080 [−0.21, +0.05]	+0.061 [−0.07, +0.19]	+0.051 [−0.08, +0.18]	−0.004 [−0.13, +0.13]	+0.072 [−0.06, +0.20]	−0.074 [−0.20, +0.05]	+0.007 [−0.12, +0.14]

ρ = Spearman correlation coefficient. Δ variables = 12-month minus preoperative values. Values are ρ with 95% confidence intervals in brackets (Fisher z transformation); $n = 232$ for all correlations except ΔLDL ($n = 231$) and ΔHbA1c ($n = 229$), for which pairs with missing values were excluded. At 12 months, %TWL ranged from 11.0% to 48.3% (9 patients [3.9%] < 20%) and %EWL from 21.4% to 115.2% (19 patients [8.2%] < 50%); associations outside this range cannot be assessed. No correlation survived Benjamini–Hochberg false discovery rate correction. %EWL, percentage excess weight loss; %TWL, percentage total weight loss; NLR, neutrophil-to-lymphocyte ratio; PLR, platelet-to-lymphocyte ratio; LDL, low-density lipoprotein; CRP, C-reactive protein; HbA1c, glycated hemoglobin; ALT, alanine aminotransferase; TSH, thyroid-stimulating hormone; fT3, free triiodothyronine; fT4, free thyroxine. Bold value indicates a raw $p < 0.05$.
*Raw $p < 0.05$.

TABLE 4 Multiple linear regression: baseline values and other correlates of thyroid hormone changes ($n = 231$).

Covariate	β (Model A) (%EWL)	95% CI (%EWL)	p (%EWL)	β (Model B) (%TWL)	95% CI (%TWL)	p (%TWL)
Dependent: ΔTSH (Adj R^2 Model A = 0.464 | Model B = 0.464)						
Baseline TSH	−0.668	[−0.817, −0.518]	<0.001*	−0.668	[−0.814, −0.512]	<0.001*
Hypothyroidism status	+0.376	[−0.125, +0.975]	0.016*	+0.371	[−0.119, +0.954]	0.017*
ΔFerritin	−0.0018	[−0.0037, −0.0001]	0.026*	−0.0018	[−0.0036, −0.0004]	0.026*
Age	+0.003	[−0.006, +0.014]	0.508	+0.003	[−0.008, +0.014]	0.527
Weight loss metric	−0.001	[−0.006, +0.003]	0.590	−0.003	[−0.015, +0.009]	0.669
Dependent: ΔfT3 (Adj R^2 Model A = 0.324 | Model B = 0.324)						
Baseline fT3	−0.581	[−0.719, −0.456]	<0.001*	−0.582	[−0.718, −0.450]	<0.001*
ΔFerritin	+0.0008	[−0.00003, +0.00145]	0.051	+0.0008	[−0.00002, +0.00151]	0.040*
Age	−0.0011	[−0.0059, +0.0037]	0.651	−0.0013	[−0.0066, +0.0035]	0.588
Weight loss metric	+0.0004	[−0.0018, +0.0026]	0.754	−0.0010	[−0.0076, +0.0052]	0.761
Dependent: ΔfT4 (Adj R^2 Model A = 0.302 | Model B = 0.303)						
Baseline fT4	−0.519	[−0.609, −0.369]	<0.001*	−0.519	[−0.614, −0.363]	<0.001*
Age	−0.0018	[−0.0037, +0.0002]	0.092	−0.0019	[−0.0039, +0.0001]	0.078
Weight loss metric	−0.0005	[−0.0017, +0.0007]	0.351	−0.0015	[−0.0047, +0.0015]	0.298

Model A includes %EWL as the weight-loss metric; Model B includes %TWL. Both models include: age, sex, DM, HT, hypothyroidism status, baseline TSH/fT3/fT4, ΔLDL, ΔCRP, ΔFerritin, and ΔNLR ($n = 231$). β is expressed per unit of each covariate (per percentage point for the weight-loss metric, per ng/mL for ΔFerritin, per year for age, and present vs. absent for hypothyroidism status), in μIU/mL for ΔTSH, pg/mL for ΔfT3, and ng/dL for ΔfT4. 95% CIs derived from patient-level bootstrap resampling ($n = 2{,}000$ iterations; percentile intervals; the ΔFerritin–ΔfT3 interval is shown to additional decimals); p-values are from the parametric models. For hypothyroidism status, the bootstrap interval includes zero in both models despite a nominal $p < 0.05$, and this association is interpreted as exploratory. Similarly, for ΔFerritin in the ΔfT3 model the bootstrap interval includes zero despite a nominal $p = 0.040$ (Model B), so this borderline, model-dependent association is likewise interpreted as exploratory. This table shows all covariates reaching $p < 0.05$ in at least one model, together with age and the weight-loss metric for each outcome; no other covariate reached $p < 0.05$ in any model. Full models, including all prespecified covariates with coefficients, 95% CIs, and p-values, are provided in Supplementary Table S7; sensitivity analyses, including heteroscedasticity-consistent standard errors, exclusion of influential observations, and adjustment for preoperative ferritin, are provided in Supplementary Tables S10 and S11. The baseline coefficients are partly a consequence of mathematical coupling between each change score and its own baseline and are not interpreted as physiological effects; Oldham's method and an ANCOVA reparameterization of the ΔTSH model are reported in Supplementary Table S6 (Results, Section 3.6).
*$p < 0.05$ (nominal, unadjusted).

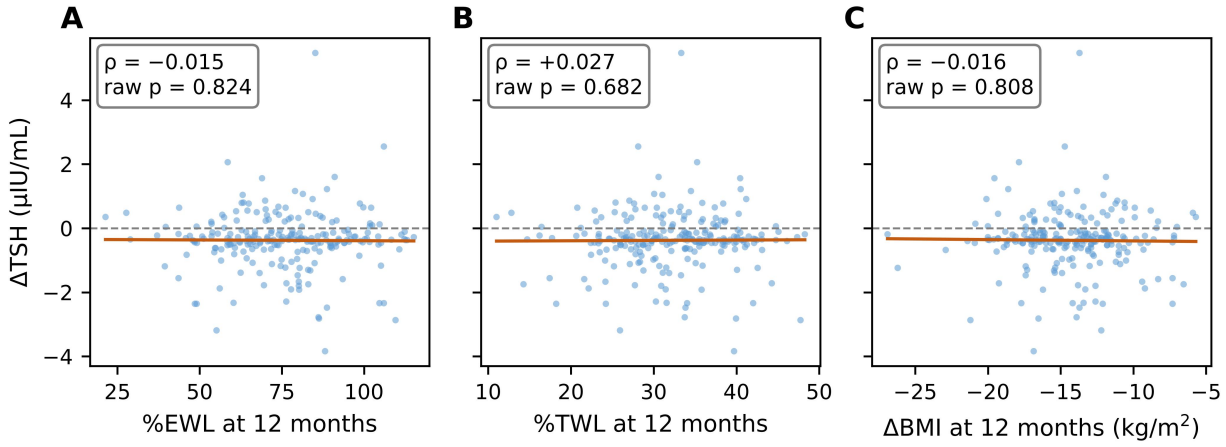


FIGURE 2
Scatter plots of 12-month TSH change (ΔTSH) against weight-loss magnitude ($n = 232$). **(A)** ΔTSH vs. percentage excess weight loss (%EWL); **(B)** ΔTSH vs. percentage total weight loss (%TWL); **(C)** ΔTSH vs. change in body mass index (ΔBMI). Spearman correlation coefficients (ρ) and unadjusted (raw) p values are shown in each panel; no association was statistically significant before or after Benjamini–Hochberg false discovery rate correction. The orange line represents an ordinary least squares regression line included for visual reference only. The dashed horizontal line indicates ΔTSH = 0. ΔTSH, change in TSH from baseline to 12 months; %EWL, percentage excess weight loss; %TWL, percentage total weight loss; ΔBMI, change in body mass index; TSH, thyroid-stimulating hormone.

parameters after correction for multiple testing (Table 3, Supplementary Figure S1). The only correlation reaching nominal (uncorrected) significance was a weak negative correlation between ΔTSH and ΔFerritin ($\rho = -0.138$ [95% CI −0.26, −0.01], raw $p = 0.035$); its sensitivity to model specification is described in Section 3.6 and Supplementary Table S10.

No statistically significant association was detected between the thyroid hormone changes and the magnitude of weight loss within the observed range. For ΔTSH, the correlations were $\rho = -0.015$ (95% CI −0.14, +0.11) with %EWL and $\rho = +0.027$ (95% CI −0.10, +0.16) with %TWL (Table 3), and $\rho = -0.016$ (raw $p = 0.808$) with the change in BMI (Figure 2). Across all four thyroid parameters, the 95% confidence intervals for the correlations with %EWL and %TWL lay between −0.15 and +0.16, so stronger correlations in either direction were not compatible with these data at the 95% confidence level. ΔTSH also did not differ significantly between patients with a preoperative BMI ≥40 and <40 kg/m^2 (Supplementary Table S4). Because %TWL at 12 months ranged from 11.0% to 48.3% and few patients had little weight loss (Section 3.1), associations outside this range cannot be assessed.

3.6 Baseline values and other correlates of thyroid hormone changes

In the multivariable models, each 12-month thyroid hormone change showed its strongest association with its own baseline value: higher preoperative TSH, fT3, and fT4 were each associated with a more negative subsequent change (a larger decrease in TSH and fT3 and a smaller increase in fT4) ($\beta = -0.668$, −0.581, and −0.519, respectively; all $p < 0.001$; Table 4, Supplementary Figure S2). Because a change score is mathematically coupled to its own baseline, these coefficients partly reflect the change-score definition, and the present analyses do not separate the contributions of coupling, measurement error, and regression to the mean; they are therefore not interpreted as physiological effects. Oldham's mean–change correlations, which address a different association from the regression coefficient, were weaker than the conventional baseline–change correlations (TSH $r = -0.23$ vs. −0.66, $p < 0.001$; fT3 $r = -0.08$ vs. −0.56, $p = 0.218$; fT4 $r = -0.12$ vs. −0.55, $p = 0.068$; Supplementary Table S6). When the ΔTSH model (Model A) was refitted as an ANCOVA with the 12-month TSH value as the outcome, the baseline TSH coefficient was +0.332, exactly 1 greater than in the change-score model, whereas all other coefficients were unchanged (Supplementary Table S6); the two specifications are reparameterizations of the same model, and their adjusted R^2 values (0.464 and 0.221) are not comparable because the outcome variables differ.

Aside from the baseline values, two covariates showed nominal associations with ΔTSH: ΔFerritin and hypothyroidism status (Table 4). ΔFerritin was negatively associated with ΔTSH (Model A: $\beta = -0.0018$ μIU/mL per ng/mL, corresponding to −0.18 μIU/mL per 100 ng/mL; bootstrap 95% CI −0.0037 to −0.0001; $p = 0.026$ in both models), such that smaller ferritin decreases accompanied larger TSH decreases; for ΔfT3, the corresponding coefficient was nominally significant in Model B only ($p = 0.040$; Model A, $p = 0.051$), with bootstrap confidence intervals that included zero, and was not significant after winsorization or adjustment for preoperative ferritin (Supplementary Table S10). The ΔTSH association persisted with heteroscedasticity-consistent (HC3) standard errors ($p = 0.046$ and 0.042), after exclusion of influential observations, and after winsorization, but was attenuated after additional adjustment for preoperative ferritin ($p = 0.166$) and when the patient with the censored LDL value, who had the largest ferritin decrease in the cohort, was included in a model without ΔLDL ($p = 0.074$ and 0.072) (Supplementary Tables S10 and S11). The ferritin association is therefore specification-dependent

and is regarded as exploratory. Hypothyroidism status had a positive coefficient for ΔTSH (Model A: $\beta = +0.376$ μIU/mL, $p = 0.016$; Model B: $\beta = +0.371$, $p = 0.017$), but its bootstrap 95% CI included zero (−0.125 to +0.975), it was not significant with HC3 standard errors ($p = 0.211$ and 0.217), and it was close to zero after exclusion of the 12 influential observations, 3 of which were from hypothyroid patients (Model A: $\beta = -0.033$) (Table 4 and Supplementary Table S11); it is therefore also regarded as exploratory.

Weight-loss magnitude, comorbidities, and the changes in inflammatory markers were not significantly associated with any thyroid change in either model; all coefficients, including those for ΔCRP and ΔNLR, are reported in Supplementary Table S7. For ΔTSH, the weight-loss coefficient was −0.001 μIU/mL per percentage point of %EWL (bootstrap 95% CI −0.006 to +0.003) and −0.003 μIU/mL per percentage point of %TWL (95% CI −0.015 to +0.009) (Table 4); rescaled to a 10-percentage-point difference in weight loss, these correspond to −0.01 μIU/mL (95% CI −0.06 to +0.03) and −0.03 μIU/mL (95% CI −0.15 to +0.09), respectively. Both intervals include zero, and associations outside them were not compatible with these data at the 95% confidence level; this does not establish equivalence. Per 10 percentage points, the corresponding estimates were +0.004 pg/mL (95% CI −0.018 to +0.026) for %EWL and −0.010 pg/mL (−0.076 to +0.052) for %TWL for ΔfT3, and −0.005 ng/dL (−0.017 to +0.007) and −0.015 ng/dL (−0.047 to +0.015), respectively, for ΔfT4 (Table 4). The six weight-loss coefficients remained non-significant with HC3 standard errors and in the models including all 232 patients; after exclusion of influential observations, one of them reached nominal significance (ΔfT4, Model A: −0.010 ng/dL per 10 percentage points of %EWL), which was not observed with %TWL or with HC3 standard errors (Supplementary Table S11). Thus, no statistically significant association between weight-loss magnitude and the thyroid hormone changes was detected within the observed range.

3.7 Hypothyroid subgroup analysis

Among the 25 patients with treated hypothyroidism, the median LT4 dose decreased from 100 to 75 mcg/day over follow-up (Friedman $p < 0.001$; Table 5). By 12 months, the dose had been reduced in 16 patients (64%; 95% CI 44.5–79.8), was unchanged in 7 (28%; 95% CI 14.3–47.6), and had been increased in 2 (8%; 95% CI 2.2–25.0). Of the 16 dose reductions, 12 were first made by 6 months and 4 between 6 and 12 months; both increases occurred by 6 months. TSH was within the laboratory reference range in 20 (80%), 22 (88%), and 24 (96%) patients preoperatively and at 6 and 12 months, and fT4 in 23 (92%), 24 (96%), and 23 (92%), respectively (Table 5). Baseline LT4 dose and 12-month weight loss did not differ significantly between patients with and without dose reduction (Supplementary Table S5); with these small numbers, this does not exclude a relationship with weight loss, and the dose changes cannot be attributed to surgery alone.

Within the subgroup, median TSH decreased from 2.67 to 2.12 μIU/mL at 6 months and 2.06 μIU/mL at 12 months (Friedman $p = 0.003$), and fT3 from 3.14 to 2.76 and 2.73 pg/mL ($p < 0.001$), whereas fT4 rose from 1.21 to 1.31 and 1.27 ng/dL ($p = 0.0498$) (Table 5). The preoperative-to-12-month TSH decrease (Hodges–Lehmann paired change −0.710 μIU/mL [95% CI −1.165, −0.150]; Supplementary Table S2) had a nominal p value of 0.021, which did not reach the Bonferroni-corrected threshold; the corresponding fT3 decrease was significant ($p < 0.001$), whereas the fT4 change was not ($p = 0.122$). Because of the small subgroup size, these estimates are imprecise, and the subgroup findings are descriptive and hypothesis-generating.

Compared with the 207 euthyroid patients, the unadjusted 12-month TSH decrease was nominally larger in the hypothyroid subgroup (median of individual changes −0.62 vs. −0.35 μIU/mL, $p = 0.017$; Hodges–Lehmann shift −0.350 μIU/mL [95% CI −0.770, −0.070]), whereas the changes in fT3 and fT4 were similar ($p = 0.602$ and 0.861) (Table 5, Supplementary Table S2). This unadjusted comparison does not account for the higher preoperative TSH in the hypothyroid subgroup; in the multivariable models, which include baseline TSH, the hypothyroidism-status coefficient was positive but not robust and is regarded as exploratory (Section 3.6, Table 4).

3.8 Sensitivity and subgroup analyses

In the analysis restricted to the 207 untreated euthyroid patients, all four thyroid parameters changed significantly over the three timepoints (all Friedman $p < 0.001$), with no statistically significant change between 6 and 12 months ($p = 0.246$–0.671); the preoperative-to-12-month paired changes were in the same direction and of similar magnitude as in the full cohort (e.g., TSH −0.330 μIU/mL [95% CI −0.385, −0.265]; Supplementary Table S9 and Table 2). No statistically significant association with weight loss was detected in this group: Spearman correlations of ΔTSH, ΔfT3, and ΔfT4 with %EWL or %TWL ranged from −0.037 to +0.011 (all $p \geq 0.59$), and in the multivariable models ($n = 206$), the weight-loss coefficients for ΔTSH were −0.0015 μIU/mL per percentage point of %EWL (95% CI −0.0056 to +0.0028) and +0.0005 μIU/mL per percentage point of %TWL (95% CI −0.0106 to +0.0120), with no weight-loss coefficient reaching significance for any outcome (all $p \geq 0.12$; Supplementary Table S9).

Excluding patients with preoperative TSH above 4.0 μIU/mL (12 patients, 5 of whom were receiving LT4) or above the upper reference limit of 4.2 μIU/mL (11 patients, 5 receiving LT4) did not change the trajectory findings: all four parameters changed significantly over time, with no statistically significant change between 6 and 12 months (Supplementary Table S3). Because these cut-offs removed only 5 of the 25 LT4-treated patients, they are not equivalent to excluding treated patients; the analysis of untreated patients above addresses that question. The thyroid hormone changes did not differ significantly by comorbidity, sex, or BMI class after correction for multiple testing; the only nominal difference, in ΔTSH by diabetes status (raw $p = 0.038$), did not survive correction (Supplementary Table S4).

4 Discussion

This study evaluated thyroid hormone dynamics, inflammatory marker changes, and their interrelationships in a cohort of 232

10.3389/fsurg.2026.1892362

TABLE 5 Hypothyroid subgroup analysis ($n = 25$, LT4 users).

Variable	Preop	6 months	12 months	Friedman χ^2 (p)	Wilcoxon pre–12 months p/r	vs. Euthyroid p (Δ)
Within-hypothyroid longitudinal changes ($n = 25$)						
LT4 dose (mcg/day)	100 [75–125]	75 [50–100]	75 [50–100]	18.00 (<0.001)**	0.001**/$r = 0.650$	–
Dose decreased	–	–	$n = 16$ (64%; 95% CI 44.5–79.8)	–	–	–
Dose unchanged	–	–	$n = 7$ (28%; 95% CI 14.3–47.6)	–	–	–
Dose increased	–	–	$n = 2$ (8%; 95% CI 2.2–25.0)	–	–	–
TSH (μIU/mL)	2.67 [1.87–3.88]	2.12 [1.24–2.84]	2.06 [1.79–2.66]	11.84 (0.003)**	0.021†/$r = 0.463$	0.017*
fT3 (pg/mL)	3.14 [2.94–3.24]	2.76 [2.53–2.89]	2.73 [2.51–3.02]	29.76 (<0.001)**	<0.001**/$r = 0.710$	0.602
fT4 (ng/dL)	1.21 [1.07–1.28]	1.31 [1.17–1.39]	1.27 [1.17–1.36]	6.00 (0.0498)*	0.122/$r = 0.310$	0.861
TSH within laboratory reference range, n (%)	20 (80%)	22 (88%)	24 (96%)	–	–	–
fT4 within laboratory reference range, n (%)	23 (92%)	24 (96%)	23 (92%)	–	–	–

Parameter	Hypothyroid ($n = 25$)	Euthyroid ($n = 207$)	p (vs. euthyroid)
Between-group comparison: 12-month change (Δ)			
ΔTSH (12 months–preop)	−0.62 [−1.32, −0.33]	−0.35 [−0.52, −0.07]	0.017*
ΔfT3 (12 months–preop)	−0.43 [−0.60, −0.26]	−0.45 [−0.64, −0.31]	0.602
ΔfT4 (12 months–preop)	0.05 [−0.02, 0.14]	0.04 [−0.02, 0.09]	0.861

CI, confidence interval; fT3, free triiodothyronine; fT4, free thyroxine; IQR, interquartile range; LT4, levothyroxine; mcg, microgram; TSH, thyroid-stimulating hormone. Values are median [IQR]; Δ values (12 months minus preoperative) are the median [IQR] of individual changes. Friedman test reported as χ^2 statistic with corresponding p-value (df = 2). Wilcoxon signed-rank test (normal approximation) for the preoperative-to-12-month within-group comparison, with effect size $r = Z/\sqrt{n}$ ($n = 25$; pairs with zero difference excluded from the calculation of Z); Mann–Whitney U test for the between-group comparison of 12-month changes (Δ) with the euthyroid group ($n = 207$); the "vs. Euthyroid p (Δ)" column repeats these p values for each parameter. Displayed p values are unadjusted; within-group pairwise comparisons between time points were assessed against the Bonferroni-corrected threshold ($\alpha = 0.017$); the between-group comparisons of 12-month changes (three parameters) are reported as nominal, unadjusted p values (ΔTSH, $p = 0.017$). Proportions of patients by dose change are shown with Wilson 95% confidence intervals; individual 12-month dose changes were −50 mcg/day ($n = 3$), −25 mcg/day ($n = 13$), 0 ($n = 7$), and +25 mcg/day ($n = 2$). Reference ranges: TSH 0.27–4.2 μIU/mL; fT4 0.92–1.68 ng/dL. Out-of-range values: TSH above the range in 5, 2 and 1 patients and below it in 0, 1 and 0 patients preoperatively and at 6 and 12 months; fT4 below the range in 2, 1 and 2 patients (none above). At 12 months, TSH was within the reference range in 15 of 16 patients with a dose reduction, 7 of 7 with an unchanged dose and 2 of 2 with a dose increase. Of the 16 patients with a dose reduction by 12 months, 12 were first reduced by 6 months (3 of whom had a further reduction between 6 and 12 months) and 4 between 6 and 12 months; both dose increases occurred by 6 months. In the between-group comparison, Δ values for the euthyroid group ($n = 207$) are shown alongside the hypothyroid group for reference. Because of the small subgroup size, estimates are imprecise; paired changes with 95% confidence intervals are provided in Supplementary Table S2.

*$p < 0.05$.

**$p < 0.01$.

†Nominal $p < 0.05$ (did not survive Bonferroni correction at $\alpha = 0.017$).

patients undergoing LSG between January 2022 and April 2025, with 12-month postoperative data. The principal findings are fourfold: (i) LSG was associated with significant reductions in TSH, fT3, and the fT3/fT4 ratio and a modest increase in fT4; changes were evident at 6 months, with no statistically significant additional change detected between 6 and 12 months; (ii) the proportion of patients with TSH >2.5 μIU/mL, a descriptive threshold, declined from 27.2% to 11.2%; (iii) no statistically significant association was detected between the thyroid hormone changes and weight-loss magnitude within the observed range, in either the correlation or the multivariable analyses, including in the 207 untreated patients; and (iv) in the small hypothyroid subgroup receiving LT4, the dose was reduced in 64% of patients (95% CI 44.5–79.8) over 12 months, a descriptive, hypothesis-generating observation. Separately, a weak association between ΔFerritin and ΔTSH was noted; it was specification-dependent and is regarded as exploratory, requiring confirmation before any role for postoperative iron status can be inferred.

4.1 Thyroid hormone changes and the fT3/fT4 ratio

The reductions in TSH and fT3 following LSG observed in our cohort are consistent with previous reports. Prior LSG-specific data likewise demonstrate significant reductions in TSH and fT3 alongside a concurrent fT4 increase at 12 months in euthyroid patients with obesity (17). A similarly concordant pattern was reported in a separate cohort of 85 euthyroid patients undergoing LSG, with significant decreases in fT3 and TSH alongside fT4 elevation at 12 months (9). A recent systematic review and meta-analysis encompassing data from 57 studies and 8,030 participants confirmed significant reductions in TSH and fT3 following sleeve gastrectomy (10). Notably, in that meta-analysis these reductions were no longer significant beyond 12 months (10); because our follow-up ended at 12 months, this later period could not be assessed in our cohort.

The behavior of fT4 merits particular emphasis. Whereas the reductions in TSH and fT3 are consistent across the reports cited above—including the pooled meta-analysis (10)—fT4 is the parameter on which individual cohorts and pooled data diverge. Our finding of a modest fT4 rise is directly concordant with the two prior LSG cohorts noted above (9, 17), yet the meta-analysis of 57 studies found no significant pooled change in fT4 at any timepoint (10). This apparent conflict may reflect heterogeneity rather than true biological inconsistency: individual sleeve-gastrectomy cohorts tend to detect a small, directionally consistent fT4 increase, whereas pooling across diverse procedures, populations, and assay platforms attenuates this modest signal toward the null. The concordance of the fT3 and TSH reductions across all these sources, contrasted with the divergent fT4 result, suggests that the fT4 response is the least consistent of the three thyroid parameters and should be interpreted with corresponding caution.

The concurrent decrease in fT3 and increase in fT4, reflected in the significant decline of the fT3/fT4 ratio, may indicate a shift in peripheral thyroid hormone metabolism. In obesity, elevated TSH and fT3/fT4 ratios have been described alongside reduced expression of the TSH receptor and altered deiodinase function in adipose tissue (17). At a mechanistic level, the deiodinase enzymes provide tissue-specific control over the peripheral conversion and inactivation of thyroid hormones: type 1 and type 2 deiodinases (D1, D2) activate T4 to the more potent T3, whereas type 3 deiodinase (D3) inactivates it, and this balance is dynamically modulated by nutritional and metabolic signals—including caloric availability and insulin—in experimental models (18). Because circulating T3 production largely depends on this deiodinase-mediated conversion, the decline in the calculated fT3/fT4 ratio we observed may reflect a downward adjustment of peripheral T4-to-T3 conversion as adipose mass and lipotoxic burden resolve (19); however, deiodinase activity was not measured in our cohort, and this interpretation remains a mechanistic hypothesis rather than a demonstrated pathway. A directionally consistent pattern is reported in a systematic review and meta-analysis of weight-loss interventions, in which successful weight reduction—whether by dietary restriction or bariatric surgery—was accompanied by decreases in fT3 and TSH alongside increases in fT4 (20). The reduction in fat mass and leptin after bariatric surgery has likewise been proposed to reduce HPT axis stimulation and to inhibit peripheral T4-to-T3 conversion (21); notably, insulin itself modulates deiodinase activity in experimental systems (18), which may connect the postoperative fall in C-peptide, a marker of insulin secretion, reported after LSG (17) to the observed thyroid changes. Additional mechanisms proposed in this context include obesity-related downregulation of adipocyte TSH receptor expression and postoperative declines in leptin, other adipokines, and ghrelin (21). None of these pathways—deiodinase activity, insulin signaling, or adipokine dynamics—was measured in the present cohort; they are presented to frame the observed changes within current physiological understanding rather than as mechanisms established by our data. Because measurements were obtained only at baseline, 6 and 12 months, and no statistically significant additional change was detected between 6 and 12 months, our data cannot establish when these changes occurred within the first 6 months or whether they represent a stable state.

4.2 TSH burden and reference ranges

TSH burden—the proportion of patients with TSH above the non-standard descriptive threshold of 2.5 μIU/mL—fell from 27.2% to 11.2% over 12 months; most values above this threshold lay within the laboratory reference range, and values above its upper limit (4.2 μIU/mL) were uncommon at all timepoints (Section 3.3). High-normal TSH within the reference range has been independently associated with obesity, dyslipidemia, hypertension, and components of the metabolic syndrome (22). A large cohort study of 9,020 US adults demonstrated that higher TSH levels were associated with increased all-cause mortality, with cardiovascular disease mediating a significant proportion of this association even in the high-normal range (23). These associations derive from observational cohorts, and our study did not assess clinical outcomes; whether the postoperative reduction in TSH has prognostic relevance therefore remains unknown. The concomitant decline in the fT3/fT4 ratio cannot be judged against a reference range, as none exists for this calculated index. Most individual TSH, fT3, and fT4 values remained within their laboratory reference ranges; at any timepoint, values outside these ranges occurred in at most 11 patients for TSH, 2 for fT3, and 14 for fT4. The decline in the ratio should not by itself be taken to indicate new thyroid dysfunction or a need for intervention.

4.3 Thyroid changes and weight-loss magnitude

No statistically significant association was detected between the thyroid hormone changes and weight-loss magnitude within the observed range, in either the correlation or the multivariable analyses, including in the 207 untreated patients (Sections 3.5, 3.6, and 3.8); this does not establish equivalence. This finding differs from that of Tian and colleagues, who reported in 256 euthyroid patients undergoing sleeve gastrectomy or Roux-en-Y gastric bypass that greater %TWL at 1 year was associated with

a greater TSH decrease (Pearson r = 0.184; adjusted standardized $\beta = 0.180$, $p = 0.008$) (21). Because ΔTSH in our study was calculated as the 12-month minus the preoperative value, an association in that direction would appear here as a negative %TWL coefficient; the estimate was −0.003 μIU/mL per percentage point (95% CI −0.015 to +0.009; Table 4). Even in the study by Tian and colleagues, %TWL explained less than 4% of the variance in ΔTSH, and differences in procedure mix (21% Roux-en-Y gastric bypass), weight loss (mean %TWL 28.3%, vs. a median of 32.2% in our cohort), and analytic approach (Pearson correlation and standardized coefficients vs. Spearman correlation and unstandardized coefficients) may contribute to the discrepancy. An external hypothesis that this cohort cannot test is that thyroid changes depend more on whether weight is lost than on how much is lost: in a dietary program, TSH decreased in euthyroid patients who lost weight and increased in those who did not (24), and in a meta-analysis, the association between weight loss and TSH, significant overall, was not significant within the bariatric surgery subgroup (20). In our cohort, %TWL was at least 11.0% in all patients and below 20% in only 9 (3.9%), so patients with little or no weight loss were not available for comparison.

Two questions should be distinguished. The cohort-level shift—TSH and fT3 declining and fT4 rising—is not readily explained by regression to the mean, because patients were not selected on the basis of extreme thyroid values; without a non-surgical control group, however, it cannot be attributed to surgery alone. The association between each baseline value and its subsequent change ($\beta = -0.668$, −0.581, and −0.519 for TSH, fT3, and fT4) is a separate matter: it partly reflects mathematical coupling, measurement error, and regression to the mean, which the present analyses do not separate, and the Oldham analysis addresses a different association rather than quantifying these contributions (Section 3.6, Supplementary Table S6). These coefficients are therefore not interpreted as physiological effects. Mechanisms proposed to link weight loss with thyroid change include reductions in leptin, altered TSH receptor expression, and growth hormone–mediated modulation of the HPT axis (20); none was measured in the present study, and they remain hypotheses. The trajectory findings were similar in the 207 untreated patients and after exclusion of patients with preoperative TSH above 4.0 μIU/mL or above the upper reference limit of 4.2 μIU/mL (Section 3.8; Supplementary Tables S3 and S9).

4.4 ΔFerritin and ΔTSH: an exploratory association

In the adjusted regression, ΔFerritin showed a nominal association with ΔTSH ($\beta = -0.0018$ μIU/mL per ng/mL, $p = 0.026$), with smaller ferritin decreases accompanying greater TSH decreases. This association was small—−0.18 μIU/mL per 100 ng/mL (bootstrap 95% CI −0.37 to −0.01), whereas most ferritin changes were much smaller than 100 ng/mL (median ΔFerritin −5.0 ng/mL, IQR −33.8 to +11.0; Supplementary Table S10)—and it was specification-dependent: it persisted with HC3 standard errors, after exclusion of influential observations, and after winsorization, but was attenuated after adjustment for preoperative ferritin ($p = 0.166$) and in a model without ΔLDL that included the patient with the censored LDL value ($p = 0.074$ and 0.072) (Section 3.6; Supplementary Tables S10 and S11). Its interpretation is further limited because ferritin is an acute-phase reactant, hemoglobin, serum iron, and transferrin saturation were not included in the extracted dataset, and postoperative iron supplementation was not recorded; changes in ferritin therefore cannot be equated with changes in iron stores. Iron is a cofactor for thyroid peroxidase (13), and iron deficiency has been associated with altered thyroid function (25), but whether postoperative iron status influences the thyroid response to LSG cannot be determined from these data. In a small LSG cohort followed for 6 months, Wang and colleagues found that the change in serum iron correlated with the change in fT4 ($r = 0.520$, $p = 0.009$) but not with the change in TSH ($r = 0.125$, $p = 0.479$) (15); differences in exposure (serum iron vs. ferritin), follow-up (6 vs. 12 months), and analysis (unadjusted correlation vs. multivariable regression) limit direct comparison with our findings.

A weaker ΔFerritin signal was seen in the ΔfT3 model (Model B: $\beta = +0.0008$, $p = 0.040$; Model A: $p = 0.051$), with smaller ferritin decreases accompanying smaller fT3 decreases; its bootstrap confidence intervals included zero, and it was not significant after winsorization, adjustment for preoperative ferritin, or inclusion of the patient with the censored LDL value (Supplementary Table S10). Because both signals derive from the same patients and were sensitive to model specification, they are regarded as exploratory and hypothesis-generating; prospective studies with serial, comprehensive iron indices would be needed to test whether iron status is related to thyroid changes after LSG.

4.5 Inflammatory marker changes

The significant reductions in NLR, PLR, and CRP over 12 months are consistent with the established anti-inflammatory effects of bariatric surgery. A retrospective study of 622 patients undergoing sleeve gastrectomy reported significant postoperative reductions in NLR (26), and a prospective cohort study reported significant declines in hs-CRP, IL-6, and other pro-inflammatory cytokines within 6 months of bariatric surgery (27). In our cohort, PLR and CRP decreased further between 6 and 12 months, whereas NLR showed no statistically significant further change (Section 3.4); the reason for this difference cannot be determined from our data. No statistically significant association was detected between the inflammatory-marker changes and the thyroid hormone changes in the correlation analyses (NLR, PLR, and CRP; Table 3) or the multivariable models (NLR and CRP; Supplementary Table S7); this does not establish that the two processes are unrelated. Zhu and colleagues, studying 88 patients 12 months after LSG, found that the TSH decrease correlated with decreases in TNF-α in euthyroid patients and with decreases in IL-6, TNF-α, and CRP in patients with subclinical hypothyroidism, whereas in euthyroid patients it did not correlate with the change in CRP (12); because our analysis included CRP, NLR, and PLR but not cytokines and was not stratified by subclinical hypothyroidism, direct comparison is limited.

4.6 Hypothyroid subgroup and LT4 dose dynamics

In the 25 LT4-treated patients, by 12 months the dose had been reduced in 16 (64%; 95% CI 44.5–79.8; 12 of them by 6 months), was unchanged in 7, and had been increased in 2, with a median decrease from 100 to 75 mcg/day; at 12 months, TSH and fT4 were within the laboratory reference range in 24 (96%) and 23 (92%) patients, respectively (Section 3.7; Table 5). The direction of these changes is consistent with previous reports: a retrospective study of hypothyroid patients undergoing LSG reported improvement or complete resolution of overt hypothyroidism in 66.7% of cases, with no patient requiring dose escalation postoperatively (28), and a comparative study found that both LSG and gastric bypass reduced LT4 requirements, with complete cessation of replacement more frequent after LSG (29). In our cohort, however, the subgroup was small, doses were adjusted at the operating surgeon's discretion without formal endocrinology referral, and the timing of LT4 intake relative to blood sampling could not be verified; the dose changes are therefore descriptive and cannot be attributed to surgery alone. Similarly, although weight loss did not differ significantly between the LT4-treated and euthyroid groups (Table 1), this does not establish the absence of treatment-related confounding in comparisons of TSH change between them. The positive coefficient for hypothyroidism status in the ΔTSH model was not robust—its bootstrap 95% CI included zero, it was not significant with HC3 standard errors, and it was close to zero after exclusion of influential observations (Table 4; Supplementary Table S11)—and is regarded as exploratory. Prospective studies with structured endocrinology co-management would be needed to define optimal LT4 titration and monitoring after LSG.

4.7 Limitations

Several limitations of this study warrant acknowledgment. The retrospective single-center design, while strengthened by a standardized surgical team, limits generalizability; because the study is observational and retrospective and lacks a non-surgical control group, causality cannot be inferred, and the observed changes cannot be attributed to surgery alone. Moreover, the analytic cohort was restricted to patients who attended the scheduled 12-month follow-up visit with complete thyroid function data at all three timepoints. The 12 patients who did not attend could not be characterized, and only 3 otherwise eligible attenders were excluded for incomplete laboratory data, too few for a formal missing-data sensitivity analysis. Selection related to follow-up may therefore limit generalizability to the broader LSG population, and its direction cannot be determined. The comparison in Supplementary Table S8 describes the patients excluded for thyroid-related eligibility criteria and does not address follow-up bias. The absence of leptin, adiponectin, ghrelin, and deiodinase activity measurements constrains mechanistic interpretation of the observed thyroid changes and precludes causal inference about the underlying pathways; future studies incorporating these biomarkers are needed to delineate the specific hormonal pathways mediating thyroid adaptation after LSG. Anti-thyroid peroxidase antibody measurements were not available for the hypothyroid subgroup, precluding formal serological confirmation of autoimmune etiology in all cases. Because thyroid function tests were obtained during routine clinical follow-up, preanalytical conditions were not standardized; although such tests are customarily drawn in the morning under fasting conditions at our institution, the exact sampling time, fasting status, timing relative to LT4 intake, and concurrent medications (e.g., proton-pump inhibitors, biotin) could not be retrospectively verified and may have introduced measurement variability. Assay-specific internal and external quality-control data for the study period were not available. LT4 dose adjustments were made by the operating surgeon without formal endocrinology referral, which, while reflecting real-world practice, may not represent optimal management. The LT4-treated subgroup was small, and its estimates are correspondingly imprecise (e.g., dose reduction in 64%, 95% CI 44.5–79.8); these findings are therefore descriptive. Several outcomes, weight-loss metrics, and covariates were examined without correction across the regression models, so isolated nominal associations, such as those of ΔFerritin and hypothyroidism status, may be chance findings; the ΔFerritin association in particular requires validation in prospective studies with serial, comprehensive iron indices. In addition, data on race/ethnicity, smoking status, alcohol consumption, and postoperative iron supplementation were not available, the last of which bears on the ferritin association discussed above. Notably, because the cohort consisted predominantly of patients with severe obesity (median baseline BMI 43.7 kg/m^2), with few patients in lower BMI ranges, the magnitude of thyroid hormone changes may differ in patients with lower-grade obesity, and our findings may not generalize across the full BMI spectrum. Similarly, few patients had little weight loss (%TWL below 20% in 9 [3.9%]), so the association between weight loss and thyroid change could not be assessed at lower levels of weight loss. Finally, the follow-up period of 12 months does not allow conclusions regarding the durability of thyroid hormone changes beyond the first postoperative year, and longer follow-up data are needed.

5 Conclusions

In this retrospective cohort of 232 patients followed for 12 months after LSG, TSH, fT3, and the calculated fT3/fT4 ratio decreased and fT4 increased modestly; changes were evident at 6 months, with no statistically significant additional change detected between 6 and 12 months. No statistically significant association was detected between the changes in TSH, fT3, and fT4 and weight-loss magnitude within the observed range, including in the 207 untreated patients, or with the changes in inflammatory markers; this does not establish that they are unrelated. The associations between each change and its own baseline value partly reflect mathematical coupling, measurement error, and regression to the mean and are not interpreted as physiological effects.

A weak, nominal association between the changes in ferritin and TSH was specification-dependent and is regarded as exploratory rather than as a basis for clinical recommendations. In LT4-treated patients, the dose was reduced in 16 of 25 (64%; 95% CI 44.5–79.8) over 12 months; given the small subgroup, this is a descriptive observation that cannot be attributed to surgery alone. Prospective, multicenter studies with longer follow-up, comprehensive iron indices, and full hormonal profiling are needed to confirm these observations and clarify the underlying mechanisms.

Data availability statement

The datasets presented in this article are not readily available because of patient privacy and institutional data-sharing restrictions; they remain available from the corresponding author on reasonable request, subject to ethical and institutional approval. Requests to access the datasets should be directed to Güney Özkaya (guneyozkaya4@outlook.com).

Ethics statement

The studies involving humans were approved by Institutional Review Board of Sancaktepe Şehit Prof. Dr. İlhan Varank Training and Research Hospital, Istanbul, Türkiye. The studies were conducted in accordance with the local legislation and institutional requirements. The ethics committee/institutional review board waived the requirement of written informed consent for participation from the participants or the participants' legal guardians/next of kin because of the retrospective design of the study and the use of de-identified clinical data obtained from routinely maintained electronic medical records. No additional patient contact or intervention was required beyond standard clinical care. The study posed minimal risk to participants, and obtaining individual informed consent was not feasible given the retrospective nature of the data collection.

Author contributions

GÖ: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. SA: Writing – review & editing, Data curation, Investigation, Methodology, Project administration. OY: Writing – review & editing, Data curation, Formal analysis, Resources. AG: Writing – review & editing, Formal analysis, Investigation, Validation. KÖÖ: Writing – review & editing, Supervision, Visualization, Writing – original draft.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. The authors acknowledge the use of Claude (version: Claude Sonnet 4.6; model: claude-sonnet-4-6; source: Anthropic, https://www.anthropic.com) for manuscript writing and editing assistance. The authors take full responsibility for the accuracy of all content, including any text, citations, and data generated or edited with AI assistance, and confirm that all AI-generated content has been reviewed for factual accuracy and is free from plagiarism.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsurg.2026.1892362/full#supplementary-material

References

1. NCD Risk Factor Collaboration (NCD-RisC). Worldwide trends in underweight and obesity from 1990 to 2022: a pooled analysis of 3663 population-representative studies with 222 million children, adolescents, and adults. *Lancet*. (2024) 403(10431):1027–50. doi: 10.1016/S0140-6736(23)02750-2

2. Rohm TV, Meier DT, Olefsky JM, Donath MY. Inflammation in obesity, diabetes, and related disorders. *Immunity*. (2022) 55(1):31–55. doi: 10.1016/j.immuni.2021.12.013

3. Mele C, Mai S, Cena T, Pagano L, Scacchi M, Biondi B, et al. The pattern of TSH and fT4 levels across different BMI ranges in a large cohort of euthyroid patients with obesity. *Front Endocrinol*. (2022) 13:1029376. doi: 10.3389/fendo.2022.1029376

4. Nannipieri M, Cecchetti F, Anselmino M, Camastra S, Niccolini P, Lamacchia M, et al. Expression of thyrotropin and thyroid hormone receptors in adipose tissue of

patients with morbid obesity and/or type 2 diabetes: effects of weight loss. *Int J Obes*. (2009) 33(9):1001–6. doi: 10.1038/ijo.2009.140

5. van Hulsteijn LT, Pasquali R, Casanueva F, Haluzik M, Ledoux S, Monteiro MP, et al. Prevalence of endocrine disorders in obese patients: systematic review and meta-analysis. *Eur J Endocrinol*. (2020) 182(1):11–21. doi: 10.1530/EJE-19-0666

6. Le Moli R, Vella V, Tumino D, Piticchio T, Naselli A, Belfiore A, et al. Inflammasome activation as a link between obesity and thyroid disorders: implications for an integrated clinical management. *Front Endocrinol*. (2022) 13:959276. doi: 10.3389/fendo.2022.959276

7. Angrisani L, Santonicola A, Iovino P, Palma R, Kow L, Prager G, et al. IFSO worldwide survey 2020-2021: current trends for bariatric and metabolic procedures. *Obes Surg*. (2024) 34(4):1075–85. doi: 10.1007/s11695-024-07118-3

8. Teke E, Güneş Y, Çoruhlu B, Esen Bulut N, Fersahoglu MM, Ergin A, et al. Effects of laparoscopic sleeve gastrectomy on thyroid hormones and relationship between metabolic parameters and long-term total weight loss. *Surg Endosc*. (2024) 38(4):1807–12. doi: 10.1007/s00464-024-10693-2

9. Chen Y, Zhang W, Pan Y, Chen W, Wang C, Yang W. Thyroid function before and after laparoscopic sleeve gastrectomy in patients with obesity. *Obes Surg*. (2022) 32(6):1954–61. doi: 10.1007/s11695-022-06035-7

10. Alreshidi NF, Eid RA, Harrabi R, Halabi WS, Albloshi AMK, Almutairi JS, et al. Time trends in thyroid hormone changes following bariatric surgery: a systematic review and meta-analysis. *Obes Surg*. (2026) 36(3):1354–68. doi: 10.1007/s11695-026-08512-9

11. Azran C, Hanhan-Shamshoum N, Irshied T, Ben-Shushan T, Dicker D, Dahan A, et al. Hypothyroidism and levothyroxine therapy following bariatric surgery: a systematic review, meta-analysis, network meta-analysis, and meta-regression. *Surg Obes Relat Dis*. (2021) 17(6):1206–17. doi: 10.1016/j.soard.2021.02.028

12. Zhu C, Gao J, Mei F, Lu L, Zhou D, Qu S. Reduction in thyroid-stimulating hormone correlated with improved inflammation markers in Chinese patients with morbid obesity undergoing laparoscopic sleeve gastrectomy. *Obes Surg*. (2019) 29(12):3954–65. doi: 10.1007/s11695-019-04063-4

13. Li S, Xu Q, Wang S, Peng H, Liu Y. Recent advances of trace elements in autoimmune thyroid disease. *Front Immunol*. (2025) 16:1662521. doi: 10.3389/fimmu.2025.1662521

14. Bjørklund G, Peana M, Pivina L, Dosa A, Aaseth J, Semenova Y, et al. Iron deficiency in obesity and after bariatric surgery. *Biomolecules*. (2021) 11(5):613. doi: 10.3390/biom11050613

15. Wang X, Fang Y, Huang X, Du L, Ren H, Sheng C, et al. Relationship of serum iron and thyroid hormone in obesity and after laparoscopic sleeve gastrectomy. *BMC Endocr Disord*. (2024) 24(1):240. doi: 10.1186/s12902-024-01753-8

16. Brethauer SA, Kim J, El Chaar M, Papasavas P, Eisenberg D, Rogers A, et al. Standardized outcomes reporting in metabolic and bariatric surgery. *Surg Obes Relat Dis*. (2015) 11(3):489–506. doi: 10.1016/j.soard.2015.02.003

17. Chen X, Zhang C, Liu W, Zhang J, Zhou Z. Laparoscopic sleeve gastrectomy-induced decreases in FT3 and TSH are related to fasting C-peptide in euthyroid patients with obesity. *Diabetes Metab Syndr Obes*. (2020) 13:4077–84. doi: 10.2147/DMSO.S277486

18. Russo SC, Salas-Lucia F, Bianco AC. Deiodinases and the metabolic code for thyroid hormone action. *Endocrinology*. (2021) 162(8):bqab059. doi: 10.1210/endocr/bqab059

19. Biondi B. Subclinical hypothyroidism in patients with obesity and metabolic syndrome: a narrative review. *Nutrients*. (2023) 16(1):87. doi: 10.3390/nu16010087

20. Nayak SS, Hashemi SM, Patel M, Shafi N, Biswas P, Javankiani S, et al. The impact of weight loss interventions on thyroid function: a systematic review and meta-analysis. *Ann Med Surg*. (2025) 87(7):4484–97. doi: 10.1097/MS9.0000000000003428

21. Tian Z, Nie Y, Li Z, Wang P, Zhang N, Hei X, et al. Total weight loss induces the alteration in thyroid function after bariatric surgery. *Front Endocrinol*. (2024) 15:1333033. doi: 10.3389/fendo.2024.1333033

22. Chang Y-C, Hua S-C, Chang C-H, Kao W-Y, Lee H-L, Chuang L-M, et al. High TSH level within normal range is associated with obesity, dyslipidemia, hypertension, inflammation, hypercoagulability, and the metabolic syndrome: a novel cardiometabolic marker. *J Clin Med*. (2019) 8(6):817. doi: 10.3390/jcm8060817

23. Inoue K, Ritz B, Brent GA, Ebrahimi R, Rhee CM, Leung AM. Association of subclinical hypothyroidism and cardiovascular disease with mortality. *JAMA Netw Open*. (2020) 3(2):e1920745. doi: 10.1001/jamanetworkopen.2019.20745

24. Croce L, Pallavicini C, Crotti S, Coperchini F, Minnelli L, Magri F, et al. Basal and longitudinal changes in serum levels of TSH in morbid obese patients experiencing failure or success of dietary treatment. *Eat Weight Disord*. (2021) 26(6):1949–55. doi: 10.1007/s40519-020-01043-x

25. Garofalo V, Condorelli RA, Cannarella R, Aversa A, Calogero AE, La Vignera S. Relationship between iron deficiency and thyroid function: a systematic review and meta-analysis. *Nutrients*. (2023) 15(22):4790. doi: 10.3390/nu15224790

26. Iwanaga TC, Santa-Cruz F, Ferraz ÁAB, Kreimer F. Impact of sleeve gastrectomy on the neutrophil-to-lymphocyte ratio and the platelet-to-lymphocyte ratio and its relationship with postoperative weight loss. *Arq Bras Cir Dig*. (2025) 38:e1882. doi: 10.1590/0102-67202025000013e1882

27. Villarreal-Calderon JR, Cuellar-Tamez R, Castillo EC, Luna-Ceron E, García-Rivas G, Elizondo-Montemayor L. Metabolic shift precedes the resolution of inflammation in a cohort of patients undergoing bariatric and metabolic surgery. *Sci Rep*. (2021) 11(1):12127. doi: 10.1038/s41598-021-91393-y

28. Almunif DS, Bamehriz F, Althuwaini S, Almigbal TH, Batais MA. The effect of laparoscopic sleeve gastrectomy on serum thyroid-stimulating hormone levels in obese patients with overt and subclinical hypothyroidism: a 7-year retrospective study. *Obes Surg*. (2020) 30(4):1491–7. doi: 10.1007/s11695-019-04337-x

29. Rudnicki Y, Slavin M, Keidar A, Kent I, Berkovich L, Tiomkin V, et al. The effect of bariatric surgery on hypothyroidism: sleeve gastrectomy versus gastric bypass. *Surg Obes Relat Dis*. (2018) 14(9):1297–303. doi: 10.1016/j.soard.2018.06.008