British Journal of Hospital Medicine

Br. J. Hosp. Med. (Lond) **2026**; 87(2): 50726
https://doi.org/10.31083/BJHM50726

Article

Development and Validation of a Nomogram for Post-Parathyroidectomy Hypocalcemia in Secondary Hyperparathyroidism

Wentian Li[1,2], Ying Wang[1], Jing Xu[2], Zhonghui Li[2,3], Peng Zhou[2,*], Qingqing He[2,*]

[1]School of Clinical Medicine, Shandong First Medical University & Shandong Academy of Medical Sciences, 250117 Jinan, Shandong, China
[2]Department of Thyroid and Breast Surgery, The 960th Hospital of the PLA Joint Logistics Support Force, 250031 Jinan, Shandong, China
[3]School of Clinical Medicine, Shandong University of Traditional Chinese Medicine, 250355 Jinan, Shandong, China
*Correspondence: weardzp@126.com (Peng Zhou); heqingqing@yeah.net (Qingqing He)
Academic Editor: John Alcolado
Submitted: 7 October 2025 Revised: 22 December 2025 Accepted: 7 January 2026 Published: 5 February 2026

Abstract

Aims/Background: Severe hypocalcemia (SH) is a common and serious complication after parathyroidectomy (PTX) in patients with secondary hyperparathyroidism (SHPT). However, accurately predicting high-risk patients remains challenging. This study aimed to develop and validate a linear predictive model to identify these patients preoperatively. **Methods**: From January 2013 to May 2025, 755 total parathyroidectomy (TPTX) or TPTX with autotransplantation (TPTX-AT) were performed by a single surgical team at the 960th Hospital of the PLA Joint Logistics Support Force. After applying inclusion and exclusion criteria, 685 patients were enrolled and randomly divided (7:3) into training and validation cohorts. Variables associated with serum calcium levels on the first postoperative day (POD1 Ca) were identified through linear regression analysis in the training cohort. Model validity was assessed using ten-fold and leave-one-out cross-validation. Bland-Altman plots and paired *t*-tests evaluated agreement within groups. Model performance in the validation cohort was measured using bias, precision, and accuracy metrics. **Results**: Significant predictors of POD1 Ca included TPTX-AT (β [95% confidence interval (CI)]: –0.055 [–0.119, –0.001]), parathyroid hormone (PTH) (–0.078 [–0.115, –0.041], ng/mL), C-terminal cross-linked telopeptide of type I collagen (CTX) (–0.147 [–0.198, –0.096], µg/L), preoperative serum calcium (0.626 [0.516, 0.736], mmol/L), and alkaline phosphatase (ALP) (–0.018 [–0.024, –0.012], µkat/L). Bland-Altman analysis showed good agreement in the validation cohort (bias <0.001, 95% limits of agreement [LoA]: –0.507, 0.566). **Conclusion**: The nomogram provides an accurate, individualized prediction of postoperative hypocalcemia risk after parathyroidectomy, supporting tailored clinical management of SHPT patients.

Keywords: parathyroidectomy; secondary hyperparathyroidism; hypocalcemia; nomogram

1. Introduction

Secondary hyperparathyroidism (SHPT), a common complication of end-stage renal disease, promotes high-turnover bone disease and extensive vascular calcification, thereby substantially increasing mortality risk [1–3]. Parathyroidectomy (PTX) is the definitive treatment for medically refractory cases, as it effectively normalizes biochemical parameters and alleviates symptoms [4]. Although PTX corrects hyperparathyroidism, the abrupt withdrawal of parathyroid hormone (PTH) often induces severe hypocalcemia (SH), defined by a serum calcium level <1.9 mmol/L [5]. This metabolic shift leads to a rapid decline in serum calcium, typically peaking on the first postoperative day [6].

Despite the high incidence of postoperative hypocalcemia, its severity cannot be reliably predicted preoperatively at the individual level. Although previous studies have associated preoperative PTH, alkaline phosphatase (ALP), and serum calcium levels with hypocalcemia risk, their predictive performance remains inconsistent across the literature [7,8]. Additionally, the contribution of specific bone turnover markers, which directly reflect underlying bone pathology, has not been fully incorporated into comprehensive predictive models. For example, a model integrating a sensitive bone formation marker such as procollagen type I N-terminal propeptide (PINP), with a specific bone resorption marker, such as C-terminal cross-linked telopeptide of type I collagen (CTX), may improve prediction of postoperative calcium decline severity. These preoperative markers may capture the extent of uncoupling between bone formation and resorption, a key mechanism in the development of hungry bone syndrome.

This study aimed to develop and validate a linear predictive model for SH on the first postoperative day in SHPT patients undergoing PTX. A clinically applicable nomogram was developed for risk stratification, personalized perioperative care, and prevention of SH-related complications.

2. Methods

2.1 Study Design

This retrospective study reviewed hospital records of SHPT patients who underwent PTX between January

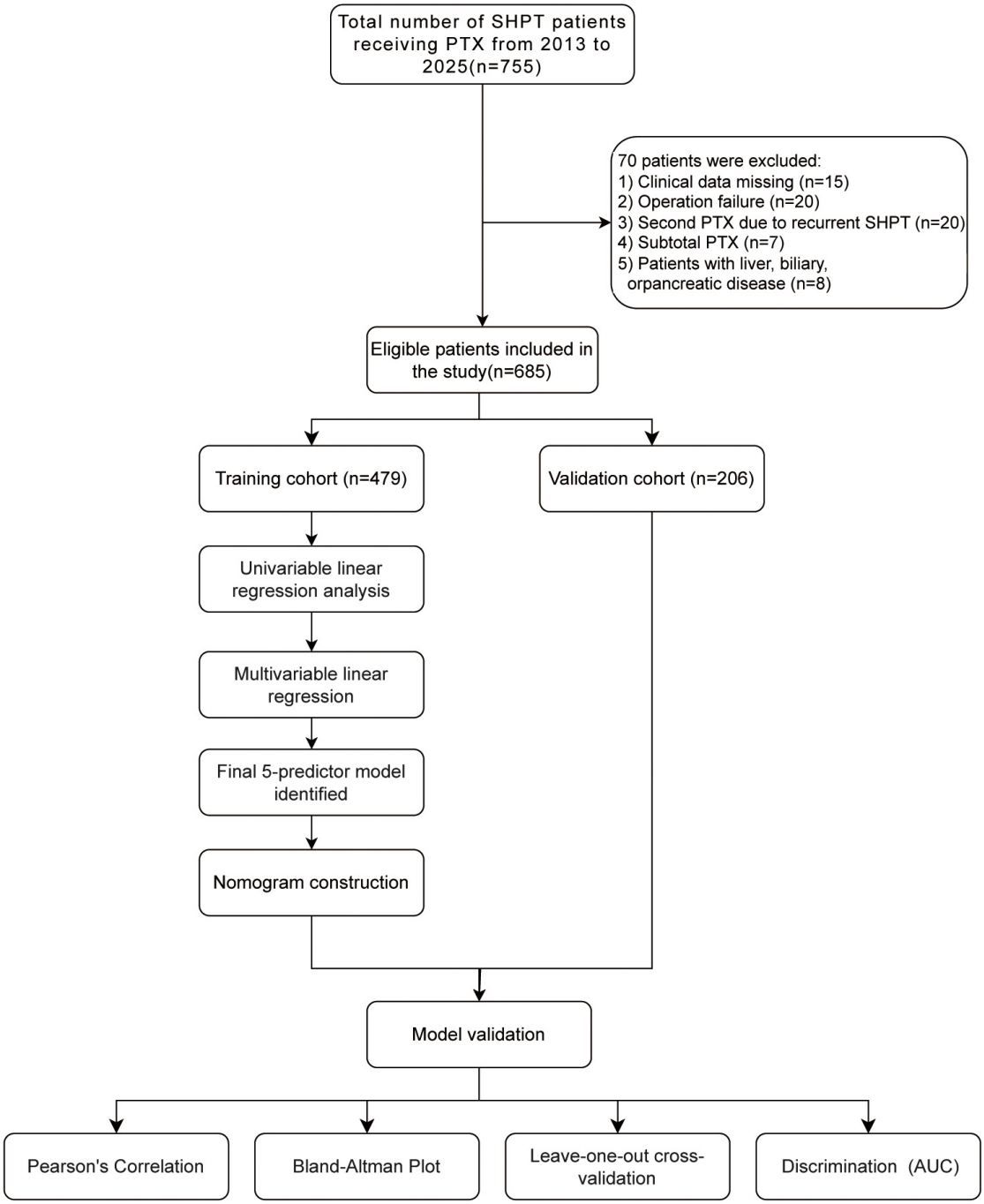

Fig. 1. The flow chart of patients' selection and the flow chart for the development, evaluation and explanation of models. SHPT, secondary hyperparathyroidism; PTX, parathyroidectomy; AUC, area under the curve.

2013 and May 2025. Dialysis patients meeting surgical indications and with complete clinical data were included. Inclusion criteria were: (1) regular dialysis at least twice weekly for more than 3 months; (2) fulfillment of at least one PTX indication, including: (a) PTH >800 pg/mL (>0.8 ng/mL); (b) medically refractory hypercalcemia or hyperphosphatemia; (c) ultrasound (US) or technetium-99m methoxyisobutylisonitrile (^{99}mTc-MIBI) scintigraphy showing $\geq$1 enlarged parathyroid gland; or (d) severe symptoms, including refractory pruritus, bone pain, ectopic calcification, or erythropoietin-resistant anemia; and (3) successful surgery. Exclusion criteria were: (1) concurrent liver, biliary, or pancreatic disease; (2) failure of PTH to decrease below 300 pg/mL (0.3 ng/mL); (3) repeat PTX for recurrent SHPT following an initial procedure; and (4) incomplete clinical records. The study workflow is illustrated in Fig. 1.

2.2 Data Collection

Patients data were retrospectively collected and analyzed, including the following variables:

(1) Preoperative data: age, gender, body mass index (BMI), dialysis modality and duration, clinical symptoms (pruritus, skeletal deformity, bone pain, height loss), medications used within six months before surgery, smoking and alcohol history, underlying diseases, comorbidities, and laboratory results (serum PTH, calcium, phosphate, potassium, ALP, complete blood count, albumin, globulin, total protein, creatinine, blood urea nitrogen, fibrinogen, procollagen type I N-terminal propeptide (PINP), osteocalcin (OST), C-terminal cross-linked telopeptide of type I collagen (CTX), and 25-hydroxyvitamin D [25(OH)D]), along with the number of parathyroid glands identified using US and ^{99}mTc-MIBI imaging.

(2) Intraoperative data: excised tissue volume, operative procedures, intraoperative PTH (ioPTH) levels at 10 and 20 min, and number of resected parathyroid glands.

(3) Postoperative data: histopathology, short-term complications, and serum PTH and calcium levels on the first postoperative day.

Since PINP and CTX frequently exceeded measurement limits in SHPT patients, these markers were classified as measurable (below the upper measurement limit) or supernormal (PINP >1200 ng/mL, CTX >6 µg/L). Corrected serum calcium may overestimate actual levels in patients undergoing long-term dialysis or those with hypoproteinemia [9,10]. Therefore, direct serum calcium measurement is recommended for accurately assessing calcium status. SH is defined by a serum calcium level <1.9 mmol/L [5] and hypocalcemia is defined as serum calcium <2.1 mmol/L [4].

2.3 Sample Size Calculation

Sample size was calculated based on two subjects per variable per regression coefficient, an established statistical approach [11]. Additionally, the four-step procedure outlined by Riley *et al*. [12] was employed to determine the required sample size. Detailed calculations and results are provided in **Supplementary Table 1**.

2.4 Perioperative Disposition

Patients underwent dialysis the day before surgery. Both preoperative and first postoperative dialysis sessions were performed without heparin. Preoperative localization relied on US and ^{99}mTc-MIBI. Surgical treatment included either total parathyroidectomy (TPTX) or TPTX with autotransplantation (TPTX-AT). The surgical team determined the procedure intraoperatively. TPTX-AT was performed if a gland appeared morphologically less hyperplastic or significantly smaller than the others. The most normal-appearing or smallest gland was selected, cut into 5–30 particles (approximately 1 mm diameter), and implanted into the sternocleidomastoid muscle [4]. Pathological examination confirmed diagnosis after complete gland removal. Intraoperative PTX levels were measured at 10- and 20-min. Surgical success was defined as resection of two or more glands accompanied by either an 80% reduction in ioPTH or serum PTH <300 pg/mL (0.3 ng/mL) within 1–3 days postoperatively [13]. On the first postoperative day, patients received intravenous calcium gluconate and oral calcium carbonate supplementation. Preoperative fasting blood samples were collected the day before surgery, while postoperative samples were obtained daily at 6–7 AM. Calcium supplementation was administered at approximately 8 AM.

2.5 Model Derivation and Validation

The dataset was divided into training and validation cohorts using a standard 7:3 ratio, consistent with previous studies demonstrating optimal performance with 70–80% training data. A linear regression model was developed to predict continuous values of serum calcium levels on the first postoperative day (POD1 Ca), preserving statistical power compared to a binary outcome model. Univariable and multivariable linear regression analyses were performed to identify variables associated with POD1 Ca levels. Independent predictors for POD1 Ca were identified using the training cohort. Initially, all variables with $p < 0.05$ in univariable analyses were included in a full regression model. Backward selection was applied, retaining variables with $p < 0.05$. A nomogram was constructed using statistically significant variables. Multicollinearity tests were performed to avoid confounding.

The multivariable model from the training cohort was applied to predict POD1 Ca in the validation cohort. Multiple methods assessed discrimination, calibration, and accuracy in the validation set, we used multiple methods to assess its discrimination, calibration and accuracy. First, Pearson correlation, paired *t*-tests, and Bland-Altman plots evaluated agreement between predicted and observed values. Internal validation was conducted using ten-fold and leave-one-out cross-validation. Second, predictive accuracy was measured using precision (interquartile range of prediction errors) and the percentages of predictions within 15% (P_{15}), 30% (P_{30}), and 50% (P_{50}) of measured values [14]. Additionally, the predicted POD1 Ca level was used to calculate the area under the curve (AUC) for discriminating between hypocalcemia and normal calcium levels, with 95% confidence intervals (CIs). The model was developed and reported according to the Transparent Reporting of a Multivariable Prediction Model for Individual Prognosis or Diagnosis (TRIPOD) checklist (**Supplementary Table 2**) [15].

2.6 Statistical Analysis

Statistical analyses were performed using SPSS version 27 (IBM, Chicago, IL, USA) and R software 4.4.2 (R Foundation for Statistical Computing, Vienna, Austria). Missing data can significantly affect data validity and reduce sample size analyses are performed [16]. For covariates with missing values less than 20% (**Supplementary Table 3**, **Supplementary Fig. 1**), multiple imputation was conducted via regression models using the R package mice

Table 1. Baseline characteristics of all patients between the training and validation cohorts.

Predictive factors	Training cohort (n = 479)	Validation cohort (n = 206)	Statistic (χ^2, Z value)	p
Age, yr (IQR)	48 (39; 55)	47.5 (38; 55)	–0.622	0.534
Gender (n%)			0.066	0.798
Male	291 (60.752%)	123 (59.709%)		
Female	188 (39.248%)	83 (40.291%)		
BMI (kg/m^2)	22.490 (20.455; 25.000)	23.065 (20.295; 25.055)	0.344	0.731
Dialysis, yr			Fisher	1.000
HD	465 (97.077%)	201 (97.573%)		
PD	9 (1.879%)	3 (1.456%)		
Both	5 (1.044%)	2 (0.971%)		
Dialysis time, yr	7 (5; 9)	7 (5; 9)	0.559	0.574
Pruritus			0.627	0.428
No	233 (48.643%)	107 (51.942%)		
Yes	246 (51.357%)	99 (48.058%)		
Skeletal deformity			0.061	0.806
No	456 (95.198%)	197 (95.631%)		
Yes	23 (4.802%)	9 (4.369%)		
Height loss			1.490	0.222
No	341 (71.190%)	156 (75.728%)		
Yes	138 (28.810%)	50 (24.272%)		
Bone pain			0.388	0.544
No	46 (9.603%)	23 (11.165%)		
Yes	433 (90.397%)	183 (88.835%)		
Cinacalcet			2.280	0.131
No	275 (57.411%)	131 (63.592%)		
Yes	204 (42.589%)	75 (36.408%)		
Calcitriol			1.633	0.201
No	221 (46.138%)	106 (51.456%)		
Yes	258 (53.862%)	100 (48.544%)		
Lanthanum carbonate			5.076	0.024
No	347 (72.443%)	166 (80.583%)		
Yes	132 (27.557%)	40 (19.417%)		
Sevelamer carbonate			1.672	0.196
No	440 (91.858%)	195 (94.660%)		
Yes	39 (8.142%)	11 (5.340%)		
Smoking history			0.964	0.326
No	437 (91.232%)	183 (88.835%)		
Yes	42 (8.768%)	23 (11.165%)		
Drinking history			0.464	0.500
No	457 (95.407%)	194 (94.175%)		
Yes	22 (4.593%)	12 (5.825%)		
Underlying diseases			Fisher	0.757
Glomerulonephritis	246 (51.357%)	107 (51.942%)		
Hypertensive nephropathy	183 (38.205%)	82 (39.806%)		
Diabetic nephropathy	11 (2.296%)	6 (2.913%)		
Polycystic kidney	10 (2.088%)	2 (0.971%)		
Others or unknown	29 (6.054%)	9 (4.369%)		
Hypertension			0.052	0.819
No	78 (16.284%)	35 (16.990%)		
Yes	401 (83.716%)	171 (83.010%)		
Diabetes			3.500	0.061
No	451 (94.154%)	197 (95.631%)		
Yes	28 (5.846%)	9 (4.369%)		
CHD			3.146	0.076
No	437 (91.232%)	196 (95.146%)		
Yes	42 (8.768%)	10 (4.854%)		

Table 1. Continued.

Predictive factors	Training cohort (n = 479)	Validation cohort (n = 206)	Statistic (χ^2, Z value)	p
Hb (g/L)	112.000 (100.000; 124.000)	113.000 (101.250; 125.750)	0.667	0.505
RBC (10^{12}/L)	3.770 (3.410; 4.190)	3.815 (3.458; 4.218)	0.973	0.331
WBC (10^9/L)	5.480 (4.540; 6.575)	5.375 (4.650; 6.530)	0.392	0.695
Neutrophil (10^9/L)	3.690 (2.960; 4.670)	3.67 (3.102; 4.568)	0.487	0.626
Monocyte (10^9/L)	0.360 (0.270; 0.460)	0.360 (0.280; 0.460)	0.537	0.591
Lymphocyte (10^9/L)	1.110 (0.910; 1.390)	1.130 (0.870; 1.438)	0.099	0.921
PLT (10^9/L)	177.000 (142.000; 215.500)	178.500 (137.250; 227.500)	0.194	0.846
Total protein (g/L)	68.600 (63.950; 74.150)	69.150 (64.325; 74.000)	0.589	0.556
Albumin (g/L)	39.500 (36.600; 42.900)	40.200 (37.000; 43.200)	1.075	0.283
Globulin (g/L)	29.000 (25.950; 32.850)	29.050 (26.700; 32.600)	0.367	0.713
ALP (μkat/L)	4.633 (2.400; 10.983)	5.367 (2.538; 9.754)	0.209	0.835
CRE (μmol/L)	886.000 (730.000; 1045.500)	865.50 (723.000; 1037.500)	–0.656	0.512
BUN (mmol/L)	23.400 (19.100; 29.200)	23.300 (17.925; 28.450)	–1.152	0.249
Serum K (mmol/L)	5.010 (4.515; 5.585)	5.000 (4.480; 5.498)	–0.450	0.653
FIB (g/L)	3.787 (3.228; 4.362)	3.720 (3.293; 4.261)	–0.728	0.466
25(OH)D (ng/mL)	16.340 (11.200; 25.730)	15.695 (10.100; 21.773)	–1.845	0.065
Row PINP (ng/mL)			2.316	0.128
≤1200	173 (36.117%)	62 (30.097%)		
>1200	306 (63.883%)	144 (69.903%)		
Row CTX (μg/L)			1.049	0.306
≤6	232 (48.434%)	91 (44.175%)		
>6	247 (51.567%)	115 (55.825%)		
OST (μg/L)	233.200 (185.150; 293.050)	232.450 (182.525; 291.725)	–0.113	0.909
Serum calcium (mmol/L)	2.470 (2.320; 2.590)	2.44 (2.292; 2.590)	–0.920	0.358
Serum phosphorus (mmol/L)	2.210 (1.940; 2.595)	2.28 (1.890; 2.615)	0.346	0.730
Serum PTH (ng/mL)	1.741 (1.119; 2.494)	1.708 (1.127; 2.328)	–0.468	0.640
ioPTH10 (ng/mL)	0.286 (0.195; 0.424)	0.286 (0.184; 0.430)	–0.125	0.901
ioPTH20 (ng/mL)	0.208 (0.143; 0.292)	0.210 (0.145; 0.288)	0.388	0.698
Oral calcium			3.570	0.059
No	12 (2.505%)	11 (5.340%)		
Yes	467 (97.495%)	195 (94.660%)		
Operative principles			1.408	0.235
TPTX	132 (27.557%)	66 (32.039%)		
TPTX-AT	347 (72.443%)	140 (67.961%)		
Frequency of US	2 (2; 3)	2 (1; 3)	–0.507	0.600
Frequency of ECT	4 (4; 4)	4 (3; 4)	–1.796	0.015
Parathyroid gland volume (cm^3)	15.100 (9.700; 23.750)	14.350 (8.900; 26.475)	–0.330	0.742
Calcification			0.693	0.405
No	422 (88.100%)	186 (90.291%)		
Yes	57 (11.900%)	20 (9.709%)		
Hemorrhagic cystic changes			Fisher	1.000
No	469 (97.912%)	202 (98.058%)		
Yes	10 (2.088%)	4 (1.942%)		
Necrosis			Fisher	0.571
No	467 (97.495%)	203 (98.544%)		
Yes	12 (2.505%)	3 (1.456%)		

IQR, interquartile range; BMI, body mass index; HD, hemodialysis; PD, peritoneal dialysis; CHD, coronary heart disease; Hb, hemoglobin; RBC, red blood cell; WBC, white blood cell; PLT, platelet; ALP, alkaline phosphatase; CRE, creatinine; BUN, blood urea nitrogen; FIB, fibrinogen; 25(OH)D, 25-hydroxyvitamin D; PINP, procollagen type I N-terminal propeptide; CTX, C-terminal cross-linked telopeptide of type I collagen; OST, osteocalcin; PTH, parathyroid hormone; ioPTH, intraoperative PTH; TPTX, total parathyroidectomy; TPTX-AT, TPTX with autotransplantation; US, ultrasound; ECT, emission computed tomography; K, potassium; yr, years.

Table 2. Linear regression results for POD1 Ca in the training cohort.

Predictive factors	Univariate logistic analysis		Multivariate logistic analysis	
	β (95% CI)	p	β (95% CI)	p
Age	0.007 (0.003, 0.011)	<0.001		
Gender				
Male	Ref			
Female	0.135 (0.064, 0.206)	<0.001		
BMI (kg/m^2)	0.009 (–0.001, 0.019)	0.058		
Dialysis, yr				
HD	Ref			
PD	0.154 (–0.103, 0.411)	0.241		
Both	–0.132 (–0.475, 0.211)	0.450		
Dialysis time, yr	0.009 (–0.001, 0.019)	0.076		
Pruritus				
No	Ref		Ref	
Yes	0.070 (0.001, 0.139)	0.049	–0.042 (–0.095, 0.011)	0.119
Skeletal deformity				
No	Ref			
Yes	–0.047 (–0.210, 0.116)	0.576		
Height loss				
No	Ref			
Yes	–0.052 (–0.128, 0.024)	0.185		
Bone pain				
No	Ref			
Yes	0.024 (–0.094, 0.142)	0.691		
Cinacalcet				
No	Ref			
Yes	–0.031 (–0.102, 0.040)	0.393		
Calcitriol				
No	Ref			
Yes	0.098 (0.029, 0.167)	0.006		
Lanthanum carbonate				
No	Ref			
Yes	0.010 (–0.068, 0.088)	0.805		
Sevelamer carbonate				
No	Ref			
Yes	0.006 (–0.121, 0.133)	0.926		
Smoking history				
No	Ref			
Yes	–0.127 (–0.25, –0.004)	0.043		
Drinking history				
No	Ref			
Yes	0.018 (–0.149, 0.185)	0.832		
Underlying diseases				
Glomerulonephritis	Ref			
Hypertensive nephropathy	0.042 (–0.032, 0.116)	0.263		
Diabetic nephropathy	–0.091 (–0.324, 0.142)	0.444		
Polycystic kidney	0.124 (–0.121, 0.369)	0.323		
Others or unknown	–0.169 (–0.318, –0.02)	0.026		
Hypertension				
No	Ref			
Yes	0.028 (–0.066, 0.122)	0.555		
Diabetes				
No	Ref			
Yes	0.082 (–0.067, 0.231)	0.278		
CHD				
No	Ref			
Yes	0.102 (–0.021, 0.225)	0.104		

Table 2. Continued.

Predictive factors	Univariate logistic analysis		Multivariate logistic analysis	
	β (95% CI)	p	β (95% CI)	p
Hb (g/L)	0.002 (0, 0.004)	0.022		
RBC (10^{12}/L)	0.038 (–0.021, 0.097)	0.204		
WBC (10^9/L)	0.023 (0.005, 0.041)	0.015		
Neutrophil (10^9/L)	0.028 (0.006, 0.05)	0.013		
Monocyte (10^9/L)	0.063 (0.01, 0.116)	0.020		
Lymphocyte (10^9/L)	–0.03 (–0.073, 0.013)	0.169		
PLT (10^9/L)	0 (0, 0)	0.108		
Total protein (g/L)	0.009 (0.005, 0.013)	<0.001		
Albumin (g/L)	0.015 (0.007, 0.023)	<0.001		
Globulin (g/L)	0.011 (0.003, 0.019)	0.002	0.005 (–0.001, 0.011)	0.057
ALP (μkat/L)	–0.028 (–0.032, –0.024)	<0.001	–0.018 (–0.024, –0.012)	<0.001
CRE (μmol/L)	0 (0, 0)	0.919		
BUN (mmol/L)	–0.002 (–0.006, 0.002)	0.442		
Serum K (mmol/L)	0.014 (–0.027, 0.055)	0.519		
FIB (g/L)	–0.089 (–0.128, –0.050)	<0.001	–0.031 (–0.062, 0)	0.051
25(OH)D (ng/mL)	–0.001 (–0.005, 0.003)	0.383		
Row PINP (ng/mL)				
≤1200	Ref			
>1200	–0.113 (–0.186, –0.04)	0.002		
Row CTX (μg/L)				
≤6	Ref		Ref	
>6	–0.164 (–0.233, –0.095)	<0.001	–0.147 (–0.198, –0.096)	<0.001
OST (μg/L)	0.002 (0.002, 0.002)	<0.001		
Serum calcium (mmol/L)	0.616 (0.479, 0.753)	<0.001	0.626 (0.516, 0.736)	<0.001
Serum phosphorus (mmol/L)	0.06 (–0.007, 0.127)	0.075		
Serum PTH (ng/mL)	–0.182 (–0.213, –0.151)	<0.001	–0.078 (–0.115, –0.041)	<0.001
ioPTH10 (ng/mL)	–0.3 (–0.394, –0.206)	<0.001		
ioPTH20 (ng/mL)	–0.594 (–0.78, –0.408)	<0.001	–0.135 (–0.296, 0.026)	0.098
Oral calcium				
No	Ref			
Yes	0.017 (–0.206, 0.24)	0.879		
Operative principles				
TPTX	Ref		Ref	
TPTX-AT	–0.134 (–0.21, –0.058)	<0.001	–0.055 (–0.119, –0.001)	0.046
Frequency of US	–0.005 (–0.034, 0.024)	0.753		
Frequency of ECT	–0.014 (–0.055, 0.027)	0.505		
Parathyroid gland volume (cm^3)	–0.025 (–0.111, 0.061)	0.572		
Calcification				
No	Ref			
Yes	–0.014 (–0.122, 0.094)	0.804		
Hemorrhagic cystic changes				
No	Ref			
Yes	–0.144 (–0.387, 0.099)	0.248		
Necrosis				
No	Ref			
Yes	–0.105 (–0.328, 0.118)	0.359		

BMI, body mass index; HD, hemodialysis; PD, peritoneal dialysis; CHD, coronary heart disease; Hb, hemoglobin; RBC, red blood cell; WBC, white blood cell; PLT, platelet; ALP, alkaline phosphatase; CRE, creatinine; BUN, blood urea nitrogen; FIB, fibrinogen; 25(OH)D, 25-hydroxyvitamin D; PINP, procollagen type I N-terminal propeptide; CTX, C-terminal cross-linked telopeptide of type I collagen; OST, osteocalcin; ioPTH, intraoperative PTH; US, ultrasound; ECT, emission computed tomography; CI, confidence interval; Ref, reference; POD1 Ca, serum calcium levels on the first postoperative day.

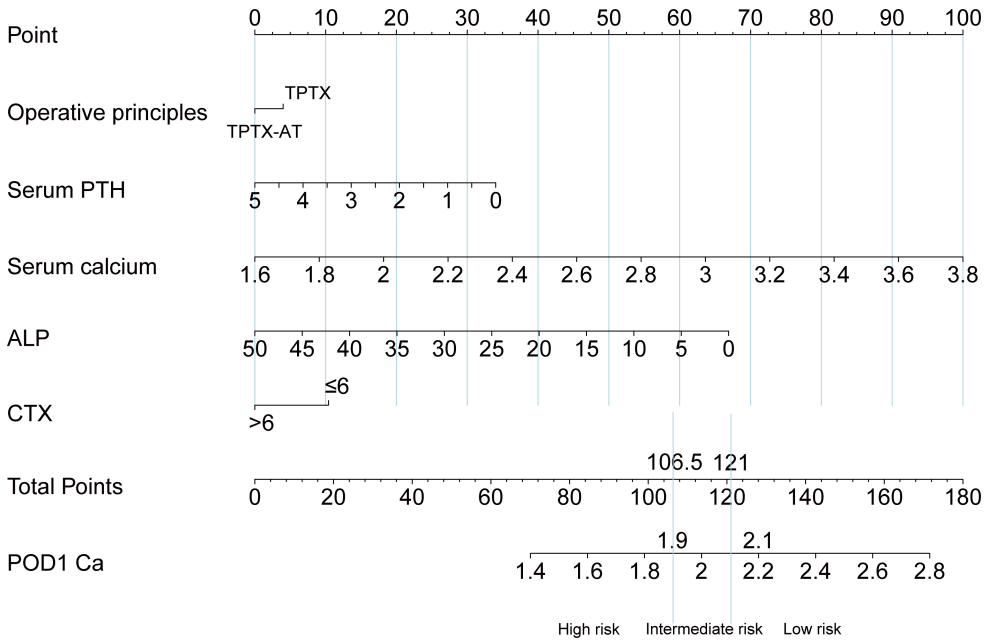

Fig. 2. Nomogram for predicting POD1 Ca after PTX.

(version 3.17.0; Stef van Buuren, TNO, The Netherlands). Normality continuous variables were assessed using the Shapiro-Wilk test. Normally distributed continuous variables are expressed as mean ± standard deviation (SD), and comparisons between groups were made using the *t*-test. Non-normally distributed continuous variables are summarized as median and interquartile range (IQR), and between group differences were evaluated by the Mann-Whitney U test. Categorical variables are reported as frequencies (percentages), with comparisons conducted using the chi-squared or Fisher's exact test. A *p*-value below 0.05 was considered statistically significant.

3. Results

3.1 Patient Characteristics

A total of 755 patients were enrolled initially, with 685 patients meeting inclusion criteria. Patients were randomly divided (7:3 ratio) into training (n = 479) and validation (n = 206) cohorts. No statistically significant differences in baseline characteristics existed between the cohorts ($p > 0.05$), except for lanthanum carbonate usage and frequency of emission computed tomography (ECT) (Table 1). Despite these differences, most variables were balanced, and the cohorts were considered comparable.

3.2 Univariable and Multivariable Analyses

Univariable and multivariable predictors of POD1 Ca are listed in Table 2. Initial univariable analysis identified 23 out of 51 potential factors significantly associated with POD1 Ca. Multivariable linear regression analysis revealed that TPTX-AT (β [95% CI]: –0.055 [–0.119, –0.001]), PTH (–0.078 [–0.115, –0.041]), CTX (–0.147 [–0.198, –0.096]), and ALP (–0.018 [–0.024, –0.012]) were significantly associated with decreased POD1 Ca. Conversely, serum calcium (0.626 [0.516, 0.736]) was significantly associated with increased POD1 Ca. Multicollinearity among predictors were assessed and found to be absent, as confirmed by variance inflation factor (VIF) values (**Supplementary Table 4**).

3.3 Model Development

The predictive model included five independent variables and was expressed by the equation: POD1 Ca = 1.075 + 0.626 × serum calcium (mmol/L) – 0.055 (TPTX-AT) – 0.078 × PTH (ng/mL) – 0.147 × CTX (μg/L) – 0.018 × ALP (μkat/L). The model was statistically significant ($F = 84.37$, $p < 0.001$). Potential collinearity was assessed VIF and tolerance values, where VIF >5 indicates problematic multicollinearity (**Supplementary Table 4**). No significant multicollinearity was detected. The significant factors identified were used to construct a nomogram predicting POD1 Ca (Fig. 2). To enhance clinical applicability, a risk stratification score was calculated. Patients were classified into low-risk, intermediate-risk, and high-risk groups based on tertiles of the total risk scores. Clinicians should suspect potential hypocalcemia or SH when nomogram scores fall below 121 (POD1 Ca <2.1 mmol/L) or 106.5 (POD1 Ca <1.9 mmol/L), respectively (**Supplementary Table 5**).

3.4 Model Performance

Model validation was conducted by comparing predicted and actual POD1 Ca levels in the validation cohort. Predicted values averaged 2.123 ± 0.247 mmol/L, while actual measurements averaged 2.093 ± 0.356 mmol/L. Fig. 3A illustrates a scatter plot of predicted versus actual POD1 Ca values, showing significant correlation ($R = 0.641$, $p < 0.001$). A paired *t*-test between predicted and

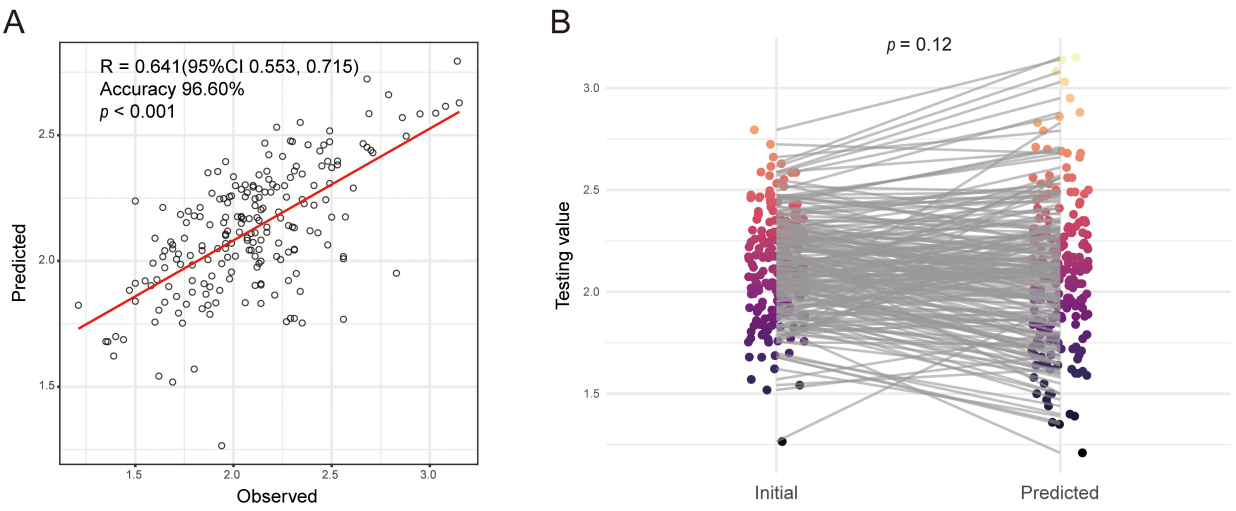

Fig. 3. Assessment of predicted and actual POD1 Ca in the validation cohort. (A) Actual vs. Predicted plot of POD1 Ca in the validation cohort. (B) Paired *t*-test for predicted and actual POD1 Ca in the validation cohort.

Table 3. Performances of the predicted POD1 Ca: bias, precision, and accuracy.

Parameter	Model
Bias (mmol/L)	
Precision (IQR)	0.054
Median of difference	0.36 (–0.14, 0.22)
Accuracy (%)	
P_{15}	73.3%
P_{30}	96.6%
P_{50}	99.5%

IQR, interquartile range; P_{15}, P_{30}, and P_{50} stand for the percentage of the estimated values within 15%, 30%, and 50% of the measured values, respectively.

actual POD1 Ca values yielded p = 0.12 (Fig. 3B). The Bland-Altman plot showed a bias of 0.030 (SD = 0.274, 95% limits of agreement: –0.507 to 0.566) (Fig. 4). Model performance is summarized in Table 3. The percentages of estimated values within P_{15}, P_{30}, and P_{50} of the measured values were 73.3%, 96.6%, and 99.5%, respectively. Leave-one-out cross-validation produced an R^2 of 0.456, Mean Absolute Error (MAE) of 0.225, Root Mean Squared Error (RMSE) of 0.287, and Mean Absolute Percentage Error (MAPE) of 10.946. Ten-fold cross-validation yielded comparable results (R^2 = 0.453, MAE = 0.226, RMSE = 0.288, MAPE = 11.012; Table 4). This strong performance in the training cohort was consistent with the model's excellent fit in the validation cohort (**Supplementary Fig. 2**).

Overall, hypocalcemia occurred in 49.8% (341/685) of patients. Within this group, SH occurred in 28.5% (195/685) of the total cohort. Clinical characteristics of patients with and without postoperative SH are presented in **Supplementary Table 6**. Patients in the hypocalcemia group showed significantly higher preoperative PTH and ALP levels and lower preoperative serum calcium levels, highlighting the need for a reliable predictive tool. The model's ability to discriminate between patients developing these outcomes was assessed using receiver operating characteristic (ROC) curve analysis. The model achieved AUC values of 0.75 (95% CI: 0.68, 0.80) for hypocalcemia and 0.81 (95% CI: 0.76, 0.87) for SH (Fig. 5). These results indicate the model's reliability and clinical utility in postoperative calcium monitoring.

4. Discussion

SHPT is a common complication in patients with end-stage renal disease. Patients with SHPT typically exhibit parathyroid hyperplasia and excessive PTH secretion, leading to disruption of bone and mineral metabolism [1]. High PTH levels mobilize bone calcium and promote ectopic calcium and phosphate deposition in vascular, cutaneous, and cardiac tissues, ultimately causing osteoporosis, fractures, pruritus, and poor clinical outcomes [2,3]. Although PTX effectively lowers serum calcium and phosphorus levels and improves prognosis [17,18], this procedure may cause various complications, among which hypocalcemia is one of the most severe. Hypocalcemia manifests as numbness, pain, seizures, low blood pressure, and potentially life-threatening conditions [19]. The reported incidence of postoperative hypocalcemia in SHPT patients ranges from 27.4% to 100% [20–22], typically occurring on the first postoperative day. Similar results were observed in our study: 341 (49.78%) of 685 patients developed hypocalcemia, and 195 (28.47%) experienced SH after the first postoperative day. Thus, close collaborative monitoring and postoperative management by thyroid surgeons, nephrologists, intensivists, and otolaryngologists are essential. However, the lack of established methods for identifying patients at high risk of hypocalcemia before surgery complicates management, highlighting the need for early SH risk stratification to improve therapeutic outcomes and reduce complications.

Table 4. Comparative assessment of model performance across groups modelization, hold-out validation, leave-one-out cross-validation, and 10-fold cross-validation.

Parameter	Modelization group	Hold-out validation group	Leave-one-out cross-validation group	10-fold cross-validation group
R^2	0.471	0.411	0.456	0.453
MAE	0.222	0.220	0.225	0.226
RMSE	0.282	0.275	0.287	0.288
MAPE	10.803	11.014	10.946	11.012
Bland–Altman plot				
bias	<0.001	<0.001		
95% LoA	0.555, 0.555	–0.507, 0.566		

R^2, R-squared; MAE, Mean Absolute Error; RMSE, Root Mean Squared Error; MAPE, Mean Absolute Percentage Error; Bland-Altman plot, a tool used to evaluate the consistency between two independent measurement methods; 95% LoA, 95% limits of agreement.

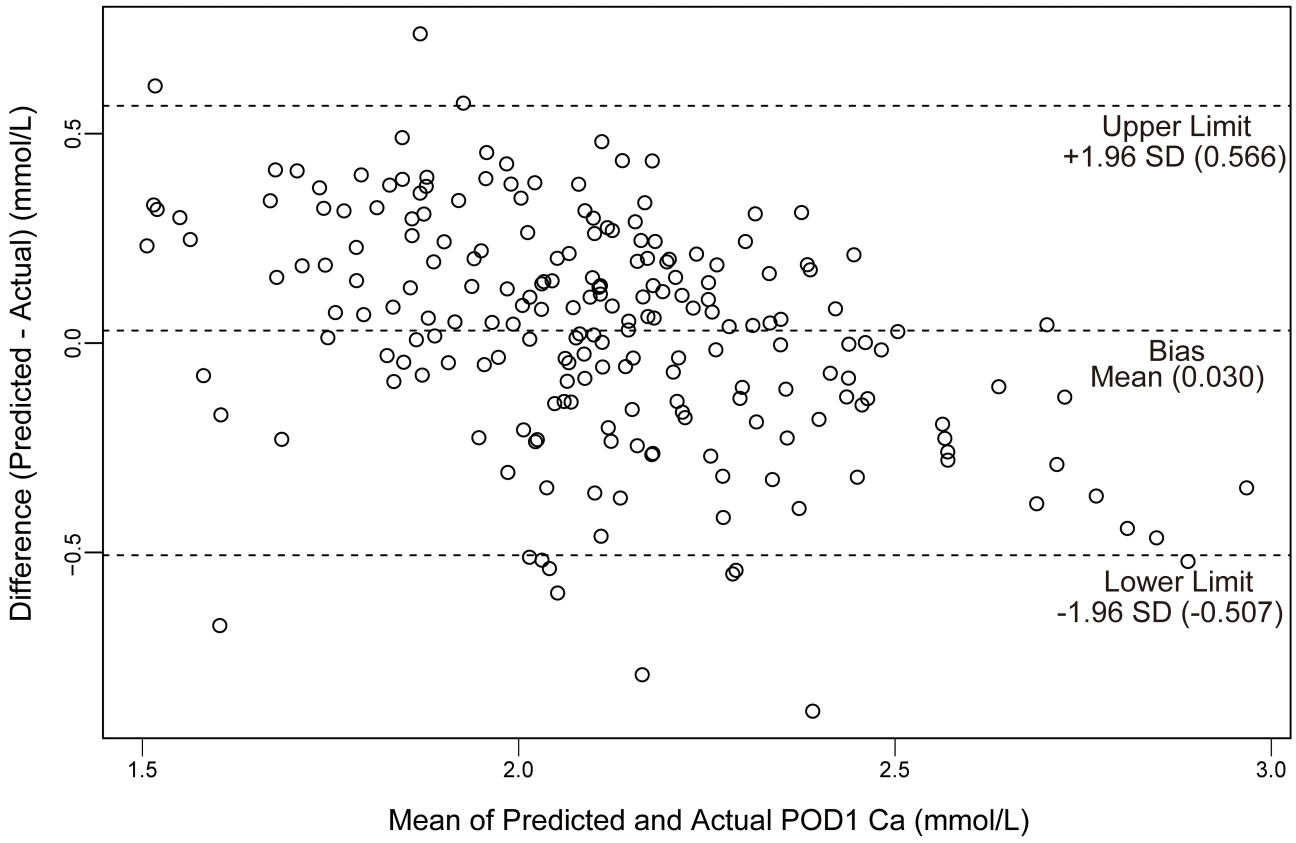

Fig. 4. Plot of differences between predicted and actual POD1 Ca versus the mean of the predicted and actual Ca in the validation cohort. SD, standard deviation; Ca, calcium.

Currently, PTH is the most common index used to evaluate SHPT severity. PTH promotes bone resorption exceeding bone formation [23], thereby increasing circulating calcium concentrations [24]. Consequently, this effect reverses immediately after PTX, causing calcium to shift abruptly from circulation into bone tissue [25,26]. Our results corroborate earlier studies linking elevated PTH levels to increased risk of hypocalcemia [27,28]. However, several other retrospective studies did not identify PTH as a significant factor for hypocalcemia development [29–31]. This discrepancy may reflect the advanced disease stage and markedly elevated PTH levels characteristic of Chinese SHPT patients undergoing delayed PTX.

The role of serum calcium as a risk factor for PTX remains controversial. In SHPT patients, lower serum calcium levels may reflect a higher baseline bone-remodeling status [32]. After PTX, patients with lower-normal calcium levels experience a more precipitous and severe drop in serum calcium. Our findings align with prior reports demonstrating a positive correlation between serum calcium and POD1 Ca [33]. Nevertheless, a separate study by Mittendorf *et al*. [34] found no correlation between preop-

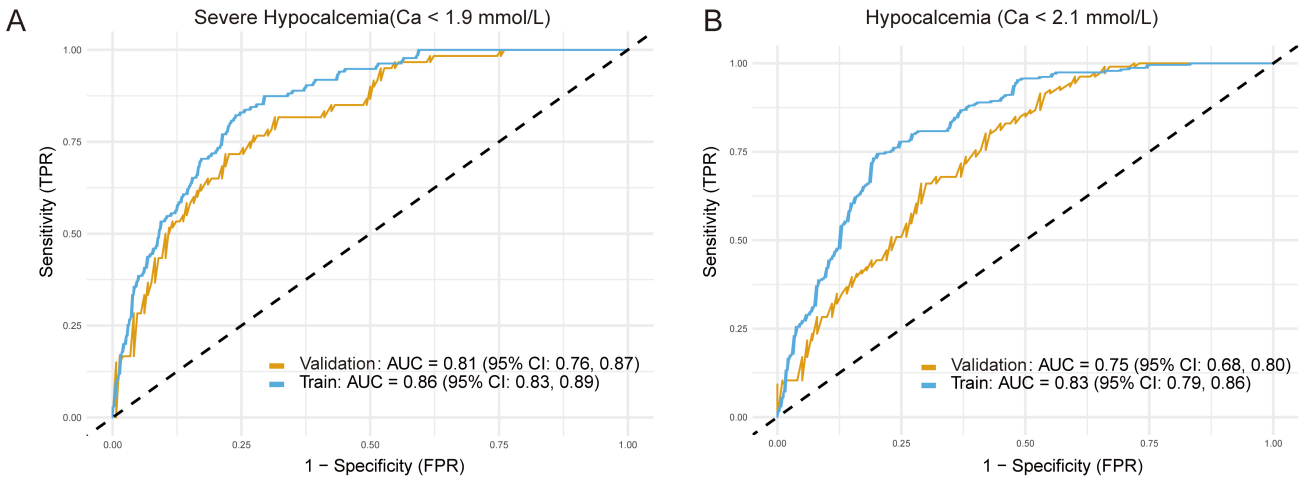

Fig. 5. ROC curves demonstrating the model's predictive performance. The figure displays the model's ability to discriminate between patients who did and did not develop (A) severe hypocalcemia (defined as serum calcium <1.9 mmol/L) and (B) hypocalcemia (defined as serum calcium <2.1 mmol/L). ROC, receiver operating characteristic; FPR, false positive rate; TPR, true positive rate.

erative and postoperative serum calcium levels. This inconsistency may be attributed to the use of corrected calcium values rather than original total serum calcium values.

Although numerous studies have reported an association between preoperative ALP levels and postoperative hypocalcemia, a consensus has not been reached regarding the predictive utility of ALP for this outcome [35]. For example, Sun *et al.* [36] reported that preoperative ALP was a risk factor for hypocalcemia and recommended its use in postoperative management. In Torer *et al.*'s study [37], high serum ALP even exerted a positive effect in preventing postoperative hypocalcemia. These discrepancies may result from variations in bone disease severity and study sample sizes. Our analysis confirms preoperative ALP as an independent predictor of hypocalcemia following PTX.

Previous research has selected CTX as a preferred marker for bone resorption due to its well-characterized assay [38]. Theoretically, higher preoperative ALP levels reflect a more active bone remodeling state, leading to a higher incidence of hypocalcemia after PTX. However, few studies indicate that CTX independently predicts hypocalcemia after PTX. Parshina *et al.* [39] demonstrated CTX as an independent risk factor for SH development following SHPT surgery, while Liu *et al.* [40] confirmed its predictive value through univariate logistic regression. In our study, CTX was included in the regression equations. If possible, preoperative CTX levels should be assessed to reflect the effect of PTX on bone turnover.

The optimal surgical approach for PTX remains controversial. According to a large meta-analysis, postoperative hypocalcemia rates are similar regardless of the type of operation; however, patients undergoing TPTX-AT might need longer periods of calcium and vitamin D supplementation [41]. Ho *et al.* [42] reported a higher incidence of hypocalcemia following TPTX, attributing this result to a more rapid postoperative decline in serum calcium levels. Surprisingly, our data indicated a lower rate of hypocalcemia after TPTX compared with TPTX-AT. These discrepancies likely reflect variations in baseline patient characteristics and differences in sample sizes. Additionally, our analysis did not include established preoperative risk factors such as gender, age, and BMI, previously associated with hypocalcemia [43]. Interestingly, despite vitamin D's well-known role in calcium and bone metabolism, our analysis did not identify preoperative 25(OH)D levels as significant predictors of postoperative hypocalcemia. This finding could be due to consistently low vitamin D levels observed in most patients with severe SHPT, thus limiting its predictive usefulness. Further studies are necessary to clarify the influence of these factors on hypocalcemia development.

The primary aim of this study is to provide clinicians with a practical tool for enhancing patient care. A key strength supporting its feasibility is that the model includes five predictive factors routinely available or easily obtainable during preoperative evaluations for PTX. Serum calcium, PTH, and ALP are standard laboratory tests. Although the CTX assay is more specialized, it is a widely recognized marker for bone turnover, increasingly used in managing severe renal bone disease. We propose embedding this assessment tool into hospital electronic health record (EHR) systems. Clinicians could utilize the nomogram in real-time during perioperative care. The EHR could automatically extract the required laboratory data, compute the risk score, and issue alerts for patients at high risk, prompting clinical teams to adjust postoperative management plans accordingly. It should be emphasized that the nomogram serves as a risk stratification tool to assist, but not replace, clinical judgment.

This study introduces a novel nomogram to predict postoperative hypocalcemia, developed using linear regression analysis. Additional strengths of the study include the following: the linear regression model provides richer,

more actionable information; the sample size (n = 685) is adequate; ten-fold cross-validation and leave-one-out cross-validation were performed, confirming the reliability of the nomogram; and patients with a total score of $\leq$106.5 were identified as a high-risk subgroup for SH.

However, this study has several limitations. Firstly, the data were collected from a single institution, limiting the generalizability of the results. Secondly, this research was retrospective. Although surgical procedures were selected based on intraoperative anatomical findings, the possibility of subtle selection biases inherent in retrospective designs cannot be completely ruled out. Thirdly, despite excluding patients with over 30% missing data and employing multiple imputation for features with less than 20% missing values, residual confounding effects may persist. Finally, other unmeasured factors potentially associated with postoperative hypocalcemia, such as parathyroid gland weight and bone mineral density, were not evaluated. Incorporating these variables should be a primary goal for future prospective studies.

5. Conclusion

In conclusion, this model demonstrates strong predictive capability by integrating preoperative hypocalcemia status, ALP, CTX, PTH, and surgical procedures. Clinicians can use this tool preoperatively to evaluate hypocalcemia risk in patients with SHPT, enabling timely interventions and improved outcome predictions.

Key Points

• This study developed and validated a nomogram to predict severe hypocalcemia on the first postoperative day in patients with secondary hyperparathyroidism undergoing parathyroidectomy.

• Multivariable linear regression identified preoperative serum calcium, parathyroid hormone, alkaline phosphatase, CTX, and surgical procedures (TPTX vs. TPTX-AT) as independent predictors.

• The model showed good calibration and internal validation, with AUCs of 0.75 for hypocalcemia and 0.81 for severe hypocalcemia.

• This nomogram enables individualized risk stratification and supports tailored perioperative calcium management to improve outcomes in SHPT patients.

Availability of Data and Materials

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

Author Contributions

WTL: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing—original draft. YW: Data curation, Investigation, Writing—original draft. JX: Investigation, Data curation. ZHL: Formal analysis. PZ: Conceptualization, Supervision, Funding acquisition. QQH: Conceptualization, Methodology, Supervision, Funding acquisition. All authors contributed to revising the manuscript critically for important intellectual content. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

This study adhered to the ethical principles for medical research involving human subjects set forth in the Declaration of Helsinki. The research protocol was reviewed and approved by the Research Ethics Committee of the 960th Hospital of the PLA Joint Logistics Support Force (Approval No. 2025-090). As a retrospective study using de-identified data, informed consent was waived. The privacy rights of all human subjects were strictly observed, with all data handled in an anonymized manner to prevent disclosure of personal information.

Acknowledgment

This study was generously supported by Jingding Medical Tech, to whom we extend our sincere gratitude. We especially thank them for providing authorization and technical support for the JD-LCPM software (V2.10, Jingding Medical Technology Co., Ltd., Hefei, China). The team at Jingding Medical Tech offered invaluable assistance in data processing. They provided valuable assistance in data processing and technical support, and did not influence or interfere with the objectivity of the results.

Funding

This work was supported by the Key Medical Discipline Project of Joint Logistics Support Force of the People's Liberation Army of China.

Conflict of Interest

The authors declare no conflict of interest.

Supplementary Material

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.31083/BJHM50726.

References

[1] Pitt SC, Sippel RS, Chen H. Secondary and tertiary hyperparathyroidism, state of the art surgical management. The Surgical Clinics of North America. 2009; 89: 1227–1239. https://doi.org/10.1016/j.suc.2009.06.011.

[2] Xu Y, Evans M, Soro M, Barany P, Carrero JJ. Secondary hyperparathyroidism and adverse health outcomes in adults with chronic kidney disease. Clinical Kidney Journal. 2021; 14: 2213–2220. https://doi.org/10.1093/ckj/sfab006.

[3] Guo W, Zhang H, Zhang Y, Huang H, Liu W, Diao Z. Low Parathyroid Hormone *Versus* Secondary Hyperparathyroidism and Survival in Patients Undergoing Hemodialysis:

A Propensity-Matched Analysis. Frontiers in Endocrinology. 2022; 13: 869330. https://doi.org/10.3389/fendo.2022.869330.

[4] Dream S, Kuo LE, Kuo JH, Sprague SM, Nwariaku FE, Wolf M, *et al*. The American Association of Endocrine Surgeons Guidelines for the Definitive Surgical Management of Secondary and Tertiary Renal Hyperparathyroidism. Annals of Surgery. 2022; 276: e141–e176. https://doi.org/10.1097/SLA.0000000000005522.

[5] Cooper MS, Gittoes NJL. Diagnosis and management of hypocalcaemia. BMJ (Clinical Research Ed.). 2008; 336: 1298–1302. https://doi.org/10.1136/bmj.39582.589433.BE.

[6] Bentrem DJ, Rademaker A, Angelos P. Evaluation of serum calcium levels in predicting hypoparathyroidism after total/near-total thyroidectomy or parathyroidectomy. The American Surgeon. 2001; 67: 249–252. https://doi.org/10.1177/000313480106700309.

[7] Cheng J, Lv Y, Zhang L, Liu Y. Construction and validation of a predictive model for hypocalcemia after parathyroidectomy in patients with secondary hyperparathyroidism. Frontiers in Endocrinology. 2022; 13: 1040264. https://doi.org/10.3389/fendo.2022.1040264.

[8] Cao L, Sun X, Zhang T, Niu Y, Suo H, Zhao Z, *et al*. A reappraisal of risk factors for early hypocalcemia after parathyroidectomy in dialysis patients. Updates in Surgery. 2022; 74: 1961–1970. https://doi.org/10.1007/s13304-022-01395-2.

[9] Lian IA, Åsberg A. Should total calcium be adjusted for albumin? A retrospective observational study of laboratory data from central Norway. BMJ Open. 2018; 8: e017703. https://doi.org/10.1136/bmjopen-2017-017703.

[10] Kato A, Takita T, Furuhashi M, Fujimoto T, Suzuki H, Hakamada M, *et al*. Influence of the assay for measuring serum albumin on corrected total calcium in chronic hemodialysis patients. Therapeutic Apheresis and Dialysis. 2011; 15: 540–546. https://doi.org/10.1111/j.1744-9987.2011.00997.x.

[11] Austin PC, Steyerberg EW. The number of subjects per variable required in linear regression analyses. Journal of Clinical Epidemiology. 2015; 68: 627–636. https://doi.org/10.1016/j.jclinepi.2014.12.014.

[12] Riley RD, Ensor J, Snell KIE, Harrell FE, Jr, Martin GP, Reitsma JB, *et al*. Calculating the sample size required for developing a clinical prediction model. BMJ (Clinical Research Ed.). 2020; 368: m441. https://doi.org/10.1136/bmj.m441.

[13] Ohe MN, Santos RO, Kunii IS, Carvalho AB, Abrahão M, Neves MCD, *et al*. Intraoperative PTH cutoff definition to predict successful parathyroidectomy in secondary and tertiary hyperparathyroidism. Brazilian Journal of Otorhinolaryngology. 2013; 79: 494–499. https://doi.org/10.5935/1808-8694.20130088.

[14] Cheng M, Zhang Q, Wang M, Huang B, Tao Y, Fan C, *et al*. A New Calculation Model for Calcium Requirements After Parathyroidectomy in Patients With Secondary Hyperparathyroidism. Clinical and Experimental Otorhinolaryngology. 2023; 16: 282–289. https://doi.org/10.21053/ceo.2023.00584.

[15] Collins GS, Moons KGM, Dhiman P, Riley RD, Beam AL, Van Calster B, *et al*. TRIPOD+AI statement: updated guidance for reporting clinical prediction models that use regression or machine learning methods. BMJ (Clinical Research Ed.). 2024; 385: e078378. https://doi.org/10.1136/bmj-2023-078378.

[16] Blazek K, van Zwieten A, Saglimbene V, Teixeira-Pinto A. A practical guide to multiple imputation of missing data in nephrology. Kidney International. 2021; 99: 68–74. https://doi.org/10.1016/j.kint.2020.07.035.

[17] Lim CTS, Kalaiselvam T, Kitan N, Goh BL. Clinical course after parathyroidectomy in adults with end-stage renal disease on maintenance dialysis. Clinical Kidney Journal. 2018; 11: 265–269. https://doi.org/10.1093/ckj/sfx086.

[18] Zhang Y, Lu Y, Feng S, Zhan Z, Shen H. Evaluation of laboratory parameters and symptoms after parathyroidectomy in dialysis patients with secondary hyperparathyroidism. Renal Failure. 2019; 41: 921–929. https://doi.org/10.1080/0886022X.2019.1666724.

[19] Witteveen JE, van Thiel S, Romijn JA, Hamdy NAT. Hungry bone syndrome: still a challenge in the post-operative management of primary hyperparathyroidism: a systematic review of the literature. European Journal of Endocrinology. 2013; 168: R45–53. https://doi.org/10.1530/EJE-12-0528.

[20] Jain N, Reilly RF. Hungry bone syndrome. Current Opinion in Nephrology and Hypertension. 2017; 26: 250–255. https://doi.org/10.1097/MNH.0000000000000327.

[21] He C, Zhang Y, Li L, Cheng G, Zhang W, Tang Y, *et al*. Risk Factor Analysis and Prediction of Severe Hypocalcemia after Total Parathyroidectomy without Auto-Transplantation in Patients with Secondary Hyperparathyroidism. International Journal of Endocrinology. 2023; 2023: 1901697. https://doi.org/10.1155/2023/1901697.

[22] Gao D, Lou Y, Cui Y, Liu S, Cui W, Sun G. Risk factors for hypocalcemia in dialysis patients with refractory secondary hyperparathyroidism after parathyroidectomy: a meta-analysis. Renal Failure. 2022; 44: 503–512. https://doi.org/10.1080/0886022X.2022.2048856.

[23] Rejnmark L, Ejlsmark-Svensson H. Effects of PTH and PTH Hypersecretion on Bone: a Clinical Perspective. Current Osteoporosis Reports. 2020; 18: 103–114. https://doi.org/10.1007/s11914-020-00574-7.

[24] Peacock M. Hypoparathyroidism and the Kidney. Endocrinology and Metabolism Clinics of North America. 2018; 47: 839–853. https://doi.org/10.1016/j.ecl.2018.07.009.

[25] Yajima A, Ogawa Y, Takahashi HE, Tominaga Y, Inou T, Otsubo O. Changes of bone remodeling immediately after parathyroidectomy for secondary hyperparathyroidism. American Journal of Kidney Diseases. 2003; 42: 729–738. https://doi.org/10.1016/s0272-6386(03)00909-0.

[26] Guo CY, Holland PA, Jackson BF, Hannon RA, Rogers A, Harrison BJ, *et al*. Immediate changes in biochemical markers of bone turnover and circulating interleukin-6 after parathyroidectomy for primary hyperparathyroidism. European Journal of Endocrinology. 2000; 142: 451–459. https://doi.org/10.1530/eje.0.1420451.

[27] Tsai WC, Peng YS, Chiu YL, Wu HY, Pai MF, Hsu SP, *et al*. Risk factors for severe hypocalcemia after parathyroidectomy in prevalent dialysis patients with secondary hyperparathyroidism. International Urology and Nephrology. 2015; 47: 1203–1207. https://doi.org/10.1007/s11255-015-1016-y.

[28] Yang M, Zhang L, Huang L, Sun X, Ji H, Lu Y. Factors predictive of critical value of hypocalcemia after total parathyroidectomy without autotransplantation in patients with secondary hyperparathyroidism. Renal Failure. 2016; 38: 1224–1227. https://doi.org/10.1080/0886022X.2016.1202731.

[29] Latus J, Roesel M, Fritz P, Braun N, Ulmer C, Steurer W, *et al*. Incidence of and risk factors for hungry bone syndrome in 84 patients with secondary hyperparathyroidism. International Journal of Nephrology and Renovascular Disease. 2013; 6: 131–137. https://doi.org/10.2147/IJNRD.S47179.

[30] Yang G, Zha X, Mao H, Yu X, Wang N, Xing C. Hypocalcemia-based prediction of hungry bone syndrome after parathyroidectomy in hemodialysis patients with refractory secondary hyperparathyroidism. The Journal of International Medical Research. 2018; 46: 4985–4994. https://doi.org/10.1177/0300060518788744.

[31] Goldfarb M, Gondek SS, Lim SM, Farra JC, Nose V, Lew JI. Postoperative hungry bone syndrome in patients with secondary hyperparathyroidism of renal origin. World Journal of Surgery. 2012; 36: 1314–1319. https://doi.org/10.1007/s00268-012-1560-x.

[32] Habas E, Sr, Eledrisi M, Khan F, Elzouki ANY. Secondary Hy-

perparathyroidism in Chronic Kidney Disease: Pathophysiology and Management. Cureus. 2021; 13: e16388. https://doi.org/10.7759/cureus.16388.

[33] Wang M, Chen B, Zou X, Wei T, Gong R, Zhu J, *et al*. A Nomogram to Predict Hungry Bone Syndrome After Parathyroidectomy in Patients With Secondary Hyperparathyroidism. The Journal of Surgical Research. 2020; 255: 33–41. https://doi.org/10.1016/j.jss.2020.05.036.

[34] Mittendorf EA, Merlino JI, McHenry CR. Post-parathyroidectomy hypocalcemia: incidence, risk factors, and management. The American Surgeon. 2004; 70: 114–120. https://doi.org/10.1177/000313480407000204.

[35] Tan PG, Ab Hadi IS, Zahari Z, Yahya MM, Wan Zain WZ, Wong MPK, *et al*. Predictors of early postoperative hypocalcemia after total parathyroidectomy in renal hyperparathyroidism. Annals of Surgical Treatment and Research. 2020; 98: 1–6. https://doi.org/10.4174/astr.2020.98.1.1.

[36] Sun X, Zhang X, Lu Y, Zhang L, Yang M. Risk factors for severe hypocalcemia after parathyroidectomy in dialysis patients with secondary hyperparathyroidism. Scientific Reports. 2018; 8: 7743. https://doi.org/10.1038/s41598-018-26142-9.

[37] Torer N, Torun D, Torer N, Micozkadioglu H, Noyan T, Ozdemir FN, *et al*. Predictors of early postoperative hypocalcemia in hemodialysis patients with secondary hyperparathyroidism. Transplantation Proceedings. 2009; 41: 3642–3646. https://doi.org/10.1016/j.transproceed.2009.06.207.

[38] Vasikaran S, Eastell R, Bruyère O, Foldes AJ, Garnero P, Griesmacher A, *et al*. Markers of bone turnover for the prediction of fracture risk and monitoring of osteoporosis treatment: a need for international reference standards. Osteoporosis International. 2011; 22: 391–420. https://doi.org/10.1007/s00198-010-1501-1.

[39] Parshina E, Kislyy P, Zulkarnaev A, Tolkach A. MO816: Bone turnover markers as risk factors of severe hypocalcemia after parathyroidectomy for secondary hyperparathyroidism. Nephrology Dialysis Transplantation. 2022; 37: gfac082-014. https://doi.org/10.1093/ndt/gfac082.014.

[40] Liu X, Li W, Huang C, Li Z. FT4 is a novel indicator for risk assessment of severe hypocalcemia following parathyroidectomy. Journal of Endocrinological Investigation. 2025; 48: 369–380. https://doi.org/10.1007/s40618-024-02460-w.

[41] Yuan Q, Liao Y, Zhou R, Liu J, Tang J, Wu G. Subtotal parathyroidectomy versus total parathyroidectomy with autotransplantation for secondary hyperparathyroidism: an updated systematic review and meta-analysis. Langenbeck's Archives of Surgery. 2019; 404: 669–679. https://doi.org/10.1007/s00423-019-01809-7.

[42] Ho LY, Wong PN, Sin HK, Wong YY, Lo KC, Chan SF, *et al*. Risk factors and clinical course of hungry bone syndrome after total parathyroidectomy in dialysis patients with secondary hyperparathyroidism. BMC Nephrology. 2017; 18: 12. https://doi.org/10.1186/s12882-016-0421-5.

[43] Cao R, Jiang H, Liang G, Zhang W. Dynamic nomogram for predicting hungry bone syndrome before parathyroidectomy. Endocrine. 2024; 83: 196–204. https://doi.org/10.1007/s12020-023-03493-6.