The value of computed tomography-based assessment of femoral neck bone mineral density in elderly hip fractures

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ABSTRACT

Background: Elderly hip fracture patients are at high risk for postoperative deep vein thrombosis (DVT). The role of femoral neck bone mineral density (BMD) assessed by computed tomography (CT) in predicting DVT remains unclear. The aim of this work was to evaluate femoral neck BMD using CT and analyze its correlation with postoperative DVT risk. ***Materials and Methods:*** This retrospective study included 130 elderly hip fracture patients, categorized into DVT (n=62) and No-DVT (n=68) groups based on postoperative ultrasound. CT X-ray absorptiometry measured BMD at admission, classifying patients as normal BMD (n=42), osteopenia (n=52), or osteoporosis (n=36). Clinical data and DVT incidence were compared. Logistic regression identified risk factors, and ROC curves assessed predictive value. ***Results:*** Overall DVT incidence was 47.69%. A significant inverse relationship existed between BMD and DVT: 21.43% (normal), 48.08% (osteopenia), and 77.78% (osteoporosis) ($P<0.05$). Univariate analysis identified age≥75, BMI≥25 kg/m², diabetes, smoking history, surgery time≥2 h, and T-score≤-2.5 as associated with DVT ($P<0.05$). Binary logistic regression confirmed these as independent risk factors ($P<0.05$). T-score≤-2.5 showed the strongest association (OR=6.176, 95% CI: 2.533-15.060). ROC analysis for the combined six indicators yielded an AUC of 0.855 (95% CI: 0.783-0.911), superior to individual indicators (AUC: 0.620-0.667). ***Conclusion:*** CT-assessed femoral neck BMD is significantly associated with postoperative DVT risk in elderly hip fracture patients and, when combined with clinical factors, provides a valuable predictive tool.

INTRODUCTION

Hip fractures primarily refer to femoral neck fractures and intertrochanteric fractures of the femur. They are a prevalent type of fragile fracture among the elderly population, with their incidence showing a continuous upward trend due to population aging, particularly notable in China and other developing countries. In the Asian region, there has been an approximate 2-to 3-fold increase in the past 30 years [1]. Epidemiological studies indicate that women have a significantly higher incidence and lifetime risk of hip fracture (18%) than men (6%) [2, 3]. Hip fractures have emerged as a significant public health issue threatening the quality of life of the elderly population, especially elderly women. Elderly hip fractures not only cause severe pain and impair limb mobility but also significantly increase the risk of deep vein thrombosis (DVT) [4].

DVT refers to a condition where blood abnormally clots within deep veins, obstructing the vascular lumen and causing venous return impairment. For elderly patients after hip fracture surgery, the risk of postoperative DVT is extremely high due to the combined effects of multiple factors, including surgical trauma, prolonged bed rest and immobilization, and a hypercoagulable state of the blood [5]. Clinical studies show that postoperative DVT occurs in 40%-60% of elderly hip fracture patients [6], while it can be reduced to around 20% after effective preventive measures are implemented [7]. DVT prolongs hospitalization, increases costs, and can cause life-threatening complications like pulmonary embolism. The study by Dubois-Silva *et al.* [8] demonstrated that among 17,742 patients with acute symptomatic pulmonary embolism complicated by lower extremity DVT, the 30-day all-cause mortality rate was 4.1%, and the pulmonary embolism-related mortality rate was 1.0%. If DVT presents with clinical symptoms, the risk of death further increases (aHR=1.52, 95% CI=1.05-2.20). Therefore, early identification and prevention of DVT is an urgent clinical priority.

Due to the gradual decline in physiological functions, the bone metabolism balance is disrupted in the elderly population, often accompanied by abnormal bone metabolism manifestations such as bone mass loss and microstructural damage of bone, which subsequently lead to a decrease in femoral neck bone mineral density (BMD). The femoral neck, as a crucial anatomical structure of the hip, not only has a close association with the occurrence of hip fractures in the elderly but may also significantly impact the patient's postoperative recovery process and the risk of complications [9]. In recent years, with the continuous advancement of medical imaging

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technologies, computed tomography (CT) technology has been widely applied in the diagnosis and evaluation of skeletal system diseases, owing to its advantages of high resolution, rapid imaging, and strong reproducibility. CT-based BMD measurement methods can accurately quantify the BMD values in the femoral neck region, providing reliable imaging evidence for the clinical assessment of bone quality. Moreover, CT-based BMD evaluation is increasingly relevant in oncology populations, where patients may undergo pelvic or abdominal CT for cancer staging or radiotherapy planning [10]. Cancer patients, especially those receiving pelvic radiotherapy, are at heightened risk for both bone loss and thromboembolic events due to direct cytotoxic effects on bone cells, vascular injury, and systemic hypercoagulability. Radiotherapy-induced bone damage and subsequent BMD decline may further exacerbate DVT risk, underscoring the clinical relevance of CT-assessed BMD in this vulnerable subgroup.

However, at present, in clinical practice, research on the association between femoral neck BMD and the risk of postoperative DVT is still in the preliminary exploration stage, lacking systematic clinical data support. Although reduced BMD has been linked to postoperative complications, few studies have specifically examined femoral neck BMD as a predictor of DVT [11, 12]. Additionally, in clinical practice, doctors' assessment of the risk of postoperative DVT often centers on traditional risk factors such as age, underlying diseases, and surgical duration, frequently overlooking femoral neck BMD as a potentially significant risk indicator. This leads to an incomplete and inaccurate identification of high-risk individuals for postoperative DVT, thereby affecting the specificity and effectiveness of preventive measures.

Therefore, conducting a study based on CT technology to evaluate femoral neck BMD in elderly patients with hip fractures and thoroughly analyzing its association with the risk of postoperative DVT holds significant clinical importance and academic value. This study aims to clarify the relationship between reduced femoral neck BMD and the risk of postoperative DVT by retrospectively analyzing the clinical data, CT imaging data, and postoperative follow-up information of 130 elderly patients with hip fractures. Notably, this study introduces several novel aspects: it is among the first to utilize CT-based femoral neck BMD assessment in a hip fracture population to evaluate its association with postoperative DVT; it integrates this imaging biomarker with established clinical risk factors into a combined predictive model; and it proposes a clinically feasible tool that leverages routinely acquired preoperative CT scans, thereby offering a practical approach for early risk stratification without additional imaging or cost.

MATERIALS AND METHODS

Study design

This retrospective comparative study analyzed 130 elderly patients with hip fractures (January 2023 -March 2025). A novel computed tomography-based X-ray absorptiometry (CTXA-Hip) approach was employed to quantitatively assess femoral neck BMD at admission. Patients were categorized into DVT (n=62) and No-DVT (n=68) groups based on postoperative ultrasound findings. Using CT-derived T-scores, patients were further classified into normal BMD (n=42), osteopenia (n=52), or osteoporosis (n=36) groups. Clinical data and DVT incidence were systematically compared among groups.

Inclusion and exclusion criteria

Inclusion criteria comprised: Age≥60 years old. Diagnosed with acute unilateral hip fracture, characterized by clinical manifestations in the affected side including pain in the femoral neck or intertrochanteric region, local swelling, functional impairment, local tenderness (+), deformity, abnormal movement, possible crepitus or bone friction sound, and possible axial percussion pain in the affected limb; a clear history of direct or indirect trauma to the hip joint; and imaging findings consistent with the clinical manifestations, with CT indicating femoral neck fracture or intertrochanteric fracture of the femur. Completion of a dedicated hip CT scan within 48 hours post-admission for BMD assessment using CTXA-Hip. Undergoing internal fixation of the fracture or hemiarthroplasty/total hip arthroplasty, with the surgery performed by the same group of senior physicians. Completion of a color Doppler ultrasound (CDUS) thrombus screening of both lower extremities at our hospital after surgery [6]. Complete clinical data. Exclusion criteria included: History of previous thrombosis. Anticoagulant/antiplatelet status. Severe comorbidities such as end-stage renal disease, active malignancy (under treatment or progression), acute infection, or sepsis. Poor quality of CT images. Pregnancy or lactation.

Ethical statement

This study is a retrospective cohort analysis, and all procedures adhere to the Declaration of Helsinki [13] and the Ethical Review Measures for Biomedical Research Involving Humans. The research protocol and data de-identification process have received formal approval from the Ethics Committee of our hospital (Approval No.:2025-093). All data export and transmission processes are encrypted and monitored by the Information Department of the hospital.

Sample size

This study primarily employed binary logistic regression analysis as the statistical method.

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According to the empirical rule for sample size estimation (at least 10 outcome events per independent variable), to detect the independent effects of six independent variables on the risk of DVT and assuming an overall DVT incidence rate of 50% [14, 15], we initially calculated that approximately 120 patients would be required to provide sufficient statistical power. Given the retrospective design of this study, we included all patients who met the criteria during the study period, ultimately enrolling a total of 130 patients. Upon verification, there were 62 DVT events in this study, resulting in an events-per-variable (EPV) ratio of 10, which meets the minimum requirement for conducting a stable and reliable binary logistic regression analysis.

Treatment methods

After admission, all patients received symptomatic Western medical treatments, including anticoagulation [with enoxaparin sodium (Sanofi, France) 0.4 g administered intravenously once daily], reducing swelling, and relieving pain. Once preoperative examinations were completed and the patient's condition was relatively stable, conventional anesthesia was performed under combined spinal-epidural anesthesia or general anesthesia. The surgical approach was selected based on the type and severity of the fracture. Before incision, 1 g of tranexamic acid (Pfizer, USA) mixed with 100 mL of 0.9% normal saline was administered intravenously. After the incision was closed, 1 g of tranexamic acid mixed with 100 mL of 0.9% normal saline was injected through the drainage tube.

Data collection and observation indicators

CT-based BMD Assessment: All patients underwent hip CT scans within 48 hours after admission. The BMD of the proximal femur and the WHO-equivalent T-score were quantitatively assessed using CTXA-Hip (16). The CT equipment used was a GE Revolution EVO 64-slice spiral CT scanner (General Electric Company, USA). Post-processing was performed using the Mindways CTXA-Hip analysis software (Version 4.2.3, Austin, TX, USA). Scan and reconstruction parameters included a tube voltage of 120 kV, slice thickness of 1 mm, and window width/level of 1600/400 HU. Prior to scanning, daily quality control was conducted using a Mindways calibration phantom, with a requirement for phantom BMD error to be<1%; otherwise, recalibration was performed. Patients were positioned supine with both feet internally rotated by 15° and restrained with straps. The scan range extended from the superior margin of the acetabulum to 5 cm below the lesser trochanter, ensuring complete inclusion of the proximal femur. Post-processing procedure: In axial images, a coronal reconstruction plane passing through the central axis of the femoral neck was manually set. The software automatically segmented three regions of interest (ROIs): the femoral neck (neck), greater trochanter (trochanter), and the entire proximal femur (total), outputting the areal BMD (mg/cm^2) and equivalent T-score for each region. If automatic segmentation was interfered with by osteophytes or metal artifacts, the ROI boundaries were manually corrected. Diagnostic criteria: According to WHO recommendations, a T-score≤−2.5 was defined as osteoporosis, and −2.5<T-score<−1.0 as osteopenia.

Postoperative DVT Assessment: When patients were suspected of having lower extremity DVT during hospitalization or at discharge, serum D-dimer levels were routinely measured. If the D-dimer level was elevated (upper limit of the normal range: 0.5 mg/L), a lower extremity CDUS examination was performed, and the diagnosis was established based on the CDUS results [17]. The incidence of DVT was compared among different BMD subgroups (normal, osteopenia, and osteoporosis).

Statistical methods

Analyzed in SPSS 26.0, with continuous variables (e.g., time from injury to surgery) assessed for normality (Shapiro-Wilk test) and presented as Mean ± SD (independent samples t-test) or Median (IQR) (Mann-Whitney U test), categorical variables (e.g., gender, underlying diseases) as n (%) (χ^2 test), and logistic regression with ROC curves used for risk prediction, all employing two-tailed tests at α=0.05.

RESULTS

The incidence of postoperative DVT in patients

Table 1 and figure 1 show that a total of 62 patients developed postoperative DVT, with an incidence rate of 47.69%. Among them, in the normal BMD subgroup consisting of 42 patients, only 9 cases developed DVT, yielding an incidence rate of 21.43%. In the osteopenia subgroup with 52 patients, 25 cases developed DVT, with an incidence rate of 48.08%. In the osteoporosis subgroup of 36 patients, 28 cases developed DVT, resulting in an incidence rate of 77.78%. The incidence of postoperative DVT in the osteopenia subgroup was higher than that in the normal BMD subgroup (χ^2=7.147, P=0.008). Moreover, the incidence of postoperative DVT in the osteoporosis subgroup was significantly higher than that in the normal BMD subgroup (χ^2=24.685, P<0.001) and the osteopenia subgroup (χ^2=24.685, P=0.005).

Table 1. Postoperative DVT incidence.

Group	No-DVT		DVT	
	n	%	n	%
Normal group (n=42)	33	78.57	9	21.43
Osteopenia group (n=52)	27	51.92	25	48.08
Osteoporosis group (n=36)	8	22.22	28	77.78

Note: DVT: Deep vein thrombosis.

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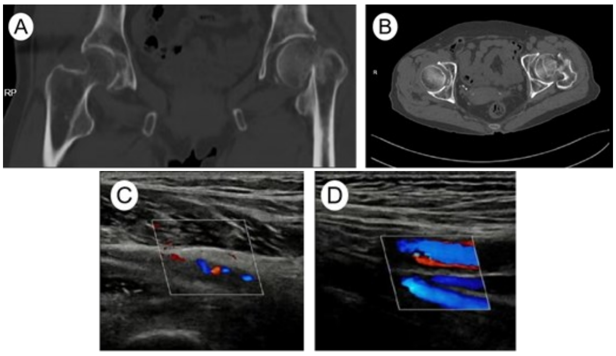

Table 2. Statistical data of the radiographic parameters (kVp and mAs values) and patient anthropometric data for selected X-ray examinations.

Univariate analysis of general data affecting DVT formation

Univariate analysis was conducted on the general clinical data, with the results presented in table 2. Among patients aged 60-74 years, there were 58 cases (85.29%) in the No-DVT group and 38 cases (61.29%) in the DVT group. Among patients aged≥75 years, there were 10 cases (14.71%) in the No-DVT group and 24 cases (38.71%) in the DVT group (χ^2=9.675, *P*=0.002), suggesting that elderly patients with hip fractures aged≥75 years have a higher risk of postoperative DVT. Among patients with a BMI<25 kg/m^2, there were 60 cases (88.24%) in the No-DVT group and 38 cases (61.29%) in the DVT group. Among patients with a BMI≥25 kg/m^2, there were 8 cases (11.76%) in the No-DVT group and 24 cases (38.71%) in the DVT group (χ^2=12.689, *P*<0.001), indicating that a BMI≥25 kg/m^2 may be one of the risk factors for postoperative DVT.

Regarding underlying diseases, a total of 44 patients had diabetes, including 14 cases (20.59%) in the No-DVT group and 30 cases (48.39%) in the DVT group (χ^2=11.193, *P*<0.001). However, the differences in the distribution of hypertension (χ^2=0.034, *P*=0.854), hyperlipidemia (χ^2=0.376, P=0.540), coronary heart disease (χ^2=0.845, *P*=0.358), and cerebrovascular disease (χ^2=0.428, *P*=0.513) histories between the two groups were not statistically significant. This suggests that elderly patients with hip fractures and comorbid diabetes have a higher risk of postoperative DVT.

Among the lifestyle-related indicators, a total of 36 patients had a smoking history, including 10 cases (14.71%) in the No-DVT group and 26 cases (41.94%) in the DVT group (χ^2=12.009, *P*<0.001). A total of 47 patients had a drinking history, including 20 cases (29.41%) in the No-DVT group and 27 cases (43.55%) in the DVT group (χ^2=2.808, *P*=0.094). In addition, the differences in the distribution of gender (χ^2=0.004, *P*=0.948), and geographical region (χ^2=0.493, *P*=0.482) between the DVT group and the No-DVT group were not statistically significant, suggesting that these factors may not be the main influencing factors for the occurrence of postoperative DVT.

Table 2. Univariate analysis of general data affecting DVT formation.

Variables	Total (n=130)	No-DVT (n=68)	DVTgroup (n=62)	Statistic	*P*
Gender, n (%)					
Male	57(43.85)	30(44.12)	27(43.55)	χ^2=0.004	0.948
Female	73(56.15)	38(55.88)	35(56.45)		
Age, n (%)					
60-74 years	96(73.85)	58(85.29)	38(61.29)	χ^2=9.675	0.002
≥75 years	34(26.15)	10(14.71)	24(38.71)		
BMI, n (%)					
<25 kg/m²	98(75.38)	60(88.24)	38(61.29)	χ^2=12.689	<0.001
≥25 kg/m²	32(24.62)	8(11.76)	24(38.71)		
Region, n (%)					
Urban area	65(50.00)	32(47.06)	33(53.23)	χ^2=0.493	0.482
Rural area	65(50.00)	36(52.94)	29(46.77)		
Underlying diseases, n (%)					
Hypertension	66(50.77)	34(50.00)	32(51.61)	χ^2=0.034	0.854
Hyperlipidemia	39(30.00)	22(32.35)	17(27.42)	χ^2=0.376	0.540
Diabetes Mellitus	44(33.85)	14(20.59)	30(48.39)	χ^2=11.193	<0.001
Coronary heart disease	27(20.77)	12(17.65)	15(24.19)	χ^2=0.845	0.358
Cerebrovascular disease	24(18.46)	14(20.59)	10(16.13)	χ^2=0.428	0.513
History of smoking, n (%)	36(27.69)	10(14.71)	26(41.94)	χ^2=12.009	<0.001
History of alcohol consumption, n (%)	47(36.15)	20(29.41)	27(43.55)	χ^2=2.808	0.094

Note: BMI: Body mass index; DVT: Deep vein thrombosis.

Univariate analysis of surgery-related indicators affecting DVT formation

This study conducted a univariate analysis of surgical-related indicators in 130 elderly patients with hip fractures to explore their associations with the occurrence of postoperative DVT. The results are presented in table 3. Regarding the surgical duration, there were 74 patients with a surgical time of less than 2 h, including 48 cases (70.59%) in the No-DVT group and 26 cases (41.94%) in the DVT group. There were 56 patients with a surgical time of 2 h or longer, including 20 cases (29.41%) in the No-DVT group and 36 cases (58.06%) in the DVT group (χ^2=10.858, *P*<0.001), suggesting that a surgical duration of 2 h or longer may increase the risk of postoperative DVT. In terms of femoral neck BMD, there were 36 patients with a T-score of≤- 2.5 (osteoporosis), including 8 cases (11.76%) in the No-DVT group and 28 cases (45.16%) in the DVT group (χ^2=18.064, *P*<0.001), indicating that elderly patients with hip fractures and osteoporosis have a higher risk of postoperative DVT.

Among the remaining indicators, the differences in the distribution of injury type (χ^2=0.192, *P*=0.661), fracture type (χ^2=2.808, *P*=0.094), time from injury to surgery (Z=- 0.764, *P*=0.455), surgical treatment method (χ^2=1.237, *P*=0.266), anesthesia method (χ^2=0.115, *P*=0.735), intraoperative blood loss (χ^2=2.908, *P*=0.088), intraoperative blood transfusion (χ^2=2.699, *P*=0.100), and intraoperative hypothermia

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(χ^2=2.498, *P*=0.114) between the DVT group and the No-DVT group were not statistically significant.

Table 3. Univariate analysis of surgery-related indicators affecting DVT formation.

Variables	Total (n=130)	No-DVT (n=68)	DVTgroup (n=62)	Statistic	*P*
Injury type, n (%)					
High-energy damage	12 (9.23)	7 (10.29)	5 (8.06)	χ^2=0.192	0.661
Low-energy damage	118 (90.77)	61 (89.71)	57 (91.94)		
Fracture type, n (%)					
Femoral neck fracture	47 (36.15)	20 (29.41)	27 (43.55)	χ^2=2.808	0.094
Intertrochanteric fracture	83 (63.85)	48 (70.59)	35 (56.45)		
Time from injury to operation (d), M (Q_1, Q_3)	4.00 (4.00, 5.00)	4.00 (4.00, 5.00)	4.00 (3.25, 5.00)	Z=- 0.764	0.455
Types of surgical treatment, n (%)					
Internal fixation for fractures	40 (30.77)	18 (26.47)	22 (35.48)	χ^2=1.237	0.266
Hemiarthroplasty or total hip arthroplasty	90 (69.23)	50 (73.53)	40 (64.52)		
Anesthesia method, n (%)					
Epidural + sub-arachnoid block anesthesia	38 (29.23)	19 (27.94)	19 (30.65)	χ^2=0.115	0.735
General anesthesia	92 (70.77)	49 (72.06)	43 (69.35)		
Operation time, n (%)					
<2 h	74 (56.92)	48 (70.59)	26 (41.94)	χ^2=10.858	<0.001
≥2 h	56 (43.08)	20 (29.41)	36 (58.06)		
Intraoperative bleeding, n (%)					
<200 mL	95 (73.08)	54 (79.41)	41 (66.13)	χ^2=2.908	0.088
≥200 mL	35 (26.92)	14 (20.59)	21 (33.87)		
Intraoperative blood transfusion, n (%)	22 (16.92)	8 (11.76)	14 (22.58)	χ^2=2.699	0.100
Intraoperative hypothermia, n (%)	26 (20.00)	10 (14.71)	16 (25.81)	χ^2=2.498	0.114
T-score≤- 2.5, n (%)	36 (27.69)	8 (11.76)	28 (45.16)	χ^2=18.064	<0.001

Binary Logistic Regression analysis of Factors Influencing DVT Formation

Significant univariate predictors were included in a binary logistic regression to identify independent risk factors for postoperative DVT. The results are shown in Table 4. Ultimately, it was confirmed that the following factors are independent risk factors for postoperative DVT: age≥75 years [OR=3.663 (95% CI: 1.576-8.515), *P*=0.003], BMI≥25 kg/m^2 [OR=4.737 (95% CI: 1.931-11.621), *P*<0.001], a history of smoking [OR=4.189 (95% CI: 1.809-9.699), *P*<0.001], diabetes [OR=3.616 (95% CI: 1.674-7.814), *P*=0.001], a surgical duration of≥2 h [OR=3.323 (95% CI: 1.608-6.866), *P*=0.001], and T-score of≤- 2.5 [OR=6.176 (95% CI: 2.533-15.060), *P*<0.001] (table 4).

Table 4. Binary logistic regression analysis.

Variables	β	S.E.	Z	*P*	OR (95% CI)
Age≥75 years old	1.298	0.430	3.017	0.003	3.663 (1.576-8.515)
BMI≥25 kg/m^2	1.555	0.458	3.397	<0.001	4.737 (1.931-11.621)
History of smoking	1.432	0.428	3.344	<0.001	4.189 (1.809-9.699)
Diabetes Mellitus	1.285	0.393	3.270	0.001	3.616 (1.674-7.814)
Operationtime ≥ 2 h	1.201	0.370	3.244	0.001	3.323 (1.608-6.866)
T-score≤- 2.5	1.821	0.455	4.004	<0.001	6.176 (2.533-15.060)

Note: OR: Odd ratio; CI: Confidence intervals.

Prediction of the risk of postoperative DVT in elderly patients with hip fracture

To evaluate the predictive value of the independent risk factors for postoperative DVT, ROC curve analysis was employed to assess the predictive efficacy of six indicators—age≥75 years, BMI≥25 kg/m^2, history of smoking, diabetes, surgical duration≥2 h, and T-score≤- 2.5—both individually and in combination. The results are presented in table 5 and Figures 2 and 3. Among the single indicators, the femoral neck BMD T-score≤- 2.5 demonstrated the highest predictive efficacy, with an AUC of 0.667 (SE=0.037, 95% CI: 0.579-0.747). The predictive efficacies of the remaining indicators, in descending order, were as follows: surgical duration≥2 h (AUC=0.643, SE=0.042, 95% CI: 0.555-0.725), diabetes (AUC=0.639, SE=0.040, 95% CI: 0.550-0.721), history of smoking (AUC=0.636, SE=0.038, 95% CI: 0.547-0.719), BMI≥25 kg/m^2 (AUC=0.635, SE=0.037, 95% CI: 0.546-0.717), and age≥75 years (AUC=0.620, SE=0.038, 95% CI: 0.531-0.704).

All single indicators had AUC values ranging from 0.620 to 0.667 (figure 2), indicating moderate predictive efficacy when used alone. When the six indicators were combined, the predictive efficacy improved significantly, with an AUC of 0.855 (SE=0.038, 95% CI: 0.783-0.911), which was markedly higher than that of each individual indicator (figure 3). This suggests that the Joint Application of multiple indicators better predicts postoperative DVT risk in elderly hip fracture patients.

Table 5. The AUC of different indicators.

Variables	AUC	SE[a]	95% CI[b]
Age≥75 years old	0.620	0.038	0.531-0.704
BMI≥25 kg/m^2	0.635	0.037	0.546-0.717
History of smoking	0.636	0.038	0.547-0.719
Diabetes Mellitus	0.639	0.040	0.550-0.721
Operation time≥2 h	0.643	0.042	0.555-0.725
T-score≤- 2.5	0.667	0.037	0.579-0.747
Joint Application	0.855	0.038	0.783-0.911

aDeLong *et al.*, 1988; bExact Binomial Test; CI: Confidence intervals.

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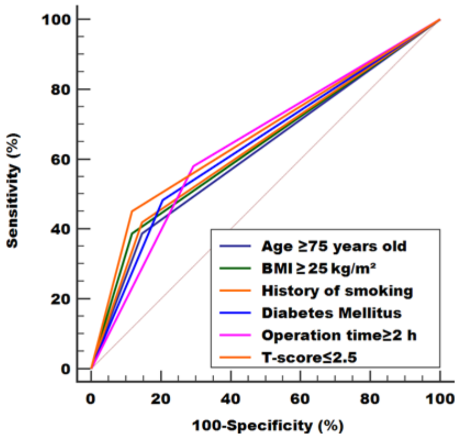

Figure 2. ROC curve of a single indicator for predicting postoperative DVT.

DISCUSSION

Despite the continuous deepening of orthopedic surgeons' understanding of fracture-related DVT and the strengthening of preventive measures over the past decade, the incidence of DVT after elderly hip fractures remains high. Existing studies have identified traditional risk factors such as age and surgical duration. However, there is still a lack of systematic evidence based on standardized imaging assessments regarding the association between femoral neck BMD, a specific bone metabolism indicator, and postoperative DVT. This study, centered on CTXA-Hip technology, delved into the association mechanism between femoral neck BMD and postoperative DVT by analyzing clinical data from 130 elderly patients with hip fractures. Additionally, it constructed a risk prediction model by incorporating indicators such as age and BMI, providing a new theoretical basis and practical approach for precise clinical prevention and control.

The pathogenic mechanisms influencing the formation of DVT include sluggish blood flow, a hypercoagulable state of the blood, and damage to the venous vessel wall. Any factors capable of inducing these three pathogenic mechanisms may potentially affect the formation of DVT [18]. The deep veins of the lower extremities run through the intermuscular spaces of the legs. During leg movements, they are subjected to increased compression by the muscles, which promotes blood to the heart. When individuals remain seated for prolonged periods or are confined to bed for an extended duration, particularly when the lower extremity muscles are relaxed and muscle strength declines, thrombi are prone to form within the lumens of the deep veins in the lower extremities. Elderly patients with hip fractures often concurrently exhibit the aforementioned three mechanisms, leading to a significantly elevated risk of developing DVT in the lower extremities. In this study, elderly patients with hip fractures underwent screening for lower extremity DVT by measuring serum D-dimer levels during their postoperative hospital stay. It was found that the incidence rate of lower extremity DVT reached 47.69% (62/130). Taoka *et al.* [19] and Qiang *et al.* [20] reported lower rates of postoperative lower extremity DVT in elderly hip fracture patients than this study. The primary reason for this discrepancy may be that, unlike in our study, DVT screening in those studies was not performed by measuring D-dimer levels; instead, the decision to conduct DVT examinations in the lower extremities was based on clinical manifestations.

The significant association between reduced BMD of the femoral neck and postoperative DVT following hip fractures in the elderly represents one of the most pivotal findings in this study. Data indicated that as the BMD grade declined from normal to osteoporosis, the incidence of postoperative DVT increased from 21.43% to 77.78%. Furthermore, binary logistic regression analysis confirmed that T-score≤- 2.5 was an independent risk factor for postoperative DVT, with a notably higher association strength (OR=6.176, 95% CI: 2.533-15.060) compared to other indicators. Multiple population-based studies and surgical cohort studies have consistently demonstrated that patients with osteoporosis face a significantly higher risk of postoperative DVT compared to those with normal BMD. A study by Miura *et al.* [21] on consecutive cases hospitalized for osteoporotic vertebral fractures found that the overall prevalence of DVT during hospitalization was 12.0%, significantly higher than historical controls of non-osteoporotic hospitalized patients in the same age group (3-5%). This study emphasized the necessity of routine DVT screening for patients with osteoporotic fractures. Similarly, the study by Li *et al.* [22] revealed that the incidence of postoperative DVT in the low-energy (osteoporotic) fracture group was 44.44%, showing no statistical difference from the high-energy trauma group (48.05%), but significantly higher than the 5-10% reported in healthy volunteers. The study suggested that the risk of DVT in low-energy fractures, which predominantly occur in osteoporotic bones, should not be overlooked. From a pathophysiological perspective, this association may stem from the multiple impairments of vascular endothelial function caused by abnormal bone metabolism [23]. In patients with osteoporosis, excessive activation of osteoclasts is closely associated with elevated levels of inflammatory factors. These factors not only promote bone resorption and disrupt bone microstructure but may also indirectly lead to vasodilation dysfunction and reduced local blood flow velocity by inhibiting the activity of eNOS and decreasing NO production through the activation of inflammatory signaling pathways [24]. Concurrently, reduced BMD of the femoral neck is often accompanied by decreased osteoblast activity and reduced secretion of the bone

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formation marker osteocalcin (OCN) [25]. As a bone-derived endocrine factor, decreased OCN levels can lead to elevated PAI-1 levels through pathways affecting insulin sensitivity, thereby inhibiting fibrinolytic system function and predisposing the blood to a hypercoagulable state (26). Additionally, in clinical practice, patients with osteoporosis often require prolonged bed rest due to slow fracture healing. A meta-analysis of 12 studies by Zhang *et al.* [27] on postoperative gynecological oncology patients showed that prolonged bed rest increased the risk of DVT by approximately 2.14-fold (OR=2.14, 95% CI: 1.56-2.94). Notably, the CTXA-Hip technique employed in this study allows for post-processing of routine hip CT images without additional radiation exposure and exhibits high sensitivity and specificity for osteoporosis diagnosis. It is highly correlated with dual-energy X-ray absorptiometry (DXA), the "gold standard" for osteoporosis diagnosis and follow-up [28]. This technical characteristic enhances its clinical utility, particularly for those requiring urgent management and unable to undergo multiple examinations.

In addition to femoral neck BMD, this study also identified five independent risk factors for postoperative DVT: age≥75 years, BMI≥25 kg/m^2, concurrent diabetes, history of smoking, and surgical duration≥2 h. Our findings revealed that patients aged≥75 years had a 3.663-fold higher risk of postoperative DVT compared to those aged 60-74 years (95% CI: 1.576-8.515). As age increases, physical motor function declines, cardiovascular function deteriorates, venous blood flow slows, and blood lipid levels rise, all of which contribute to an increased prevalence of risk factors for DVT. In elderly patients, reduced vascular elasticity and endothelial aging lead to decreased venous wall compliance, increased blood flow resistance, elevated coagulation factor levels, and decreased anticoagulant factor activity, predisposing the blood to a hypercoagulable state. An analysis by Cowan *et al.* [29] of 414,045 cases of lower extremity DVT from the TriNetX global database between 2017 and 2023 showed that individuals aged 65-90 years accounted for 58% of all cases, while those aged 0-17 years accounted for only 0.5%, confirming a significant increase in incidence with advancing age. For patients with a BMI≥25 kg/m^2, this study found a 4.737-fold higher risk of postoperative DVT compared to those with a normal BMI, a finding highly consistent with the results of Lindström *et al.* [30], who demonstrated a linear positive correlation between BMI and venous thromboembolism (VTE), with risk beginning to rise even with mild overweight. The core mechanism by which obesity increases thrombotic risk lies in the synergistic effects of physical compression of veins by lower extremity fat accumulation and metabolic disorders. Obese patients often exhibit insulin resistance, which promotes endothelial cell apoptosis, while chronic inflammation activates the coagulation system, both of which exacerbate thrombotic risk [31].

A study by Abudukadier *et al.* [32] on patients over 60 years old undergoing total hip arthroplasty found significant positive correlations between diabetes, smoking history, and postoperative lower extremity DVT formation, identifying these factors as independent risk factors for DVT development after total hip arthroplasty. The mechanisms underlying diabetes and smoking history as risk factors for postoperative DVT were further validated in this study. Our findings showed that postoperative DVT risk was 3.6 times higher in patients with diabetes. Hyperglycemia-induced endothelial damage is a key mechanism. Prolonged hyperglycemic environments generate AGEs through non-enzymatic glycation, which bind to endothelial cell surface receptors and activate oxidative stress, leading to endothelial cell apoptosis while inhibiting plasminogen activator activity and reducing blood fibrinolytic capacity [33]. Diabetic patients often suffer from peripheral neuropathy and vasculopathy, with the former causing decreased lower extremity muscle contraction and insufficient venous return, and the latter leading to venous wall thickening and luminal narrowing, further exacerbating blood stasis [34]. Regarding smoking history, this study found that patients with a history of smoking had a 4.189-fold higher risk of postoperative DVT compared to those without. The toxic effects of nicotine are the primary cause. Nicotine stimulates sympathetic nervous system excitation, leading to vasoconstriction and reduced blood flow velocity, while promoting platelet activation and aggregation. Additionally, ROS generated by smoking oxidize LDL to form ox-LDL, further damaging vascular endothelium and promoting inflammatory factor release [35]. The clinical significance of surgical duration≥2 h as an independent risk factor for postoperative DVT was fully demonstrated in this study. Data showed that patients with surgical durations≥2 h had a 3.323-fold higher risk of postoperative DVT compared to those with durations<2 h. The increased thrombotic risk associated with prolonged surgical time is primarily due to the combined effects of traumatic stress and blood stasis. On one hand, prolonged surgery increases soft tissue dissection and bone surface exposure, leading to the release of large amounts of inflammatory and coagulation factors, which activate the coagulation system. On the other hand, patients must maintain a fixed position during surgery, resulting in prolonged compression of lower extremity veins. Especially under general anesthesia, muscle relaxation further reduces venous return, predisposing to venous stasis [36].

ROC curve analysis demonstrated that when the six indicators - age≥75 years, BMI≥25 kg/m^2, concurrent diabetes, history of smoking, surgical

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duration≥2 h, and T-score≤- 2.5 - were used in combination, the AUC for predicting postoperative DVT reached as high as 0.855 (95% CI: 0.783-0.911), significantly outperforming each individual indicator (AUC: 0.620-0.667). This model exhibits substantial advantages over existing predictive tools. Currently, widely used clinical models such as the Caprini and Padua scores are primarily designed for general surgical or medical patients and do not incorporate hip fracture-specific indicators like femoral neck BMD or surgical duration, resulting in reduced predictive efficacy in elderly patients with hip fractures [37]. In contrast, our model is specifically tailored for this population and enhances predictive accuracy by integrating novel imaging biomarkers. Notably, the indicators in this model - age, BMI, smoking history, and diabetes history - can be readily obtained through patient interviews and medical record reviews, while surgical duration can be extracted from operative notes, and femoral neck BMD can be derived from routine post-processing analysis of CT images, eliminating the need for additional examinations. From a clinical application perspective, the ease of obtaining these indicators underscores the model's significant practical value.

Study limitations

Despite its meaningful results, this single-center retrospective study may have selection bias and unmeasured confounders. Future multi-center, prospective studies are needed to validate the link between femoral neck BMD and postoperative DVT. Additionally, this study only established statistical associations between risk factors and DVT without conducting basic experimental investigations into the molecular mechanisms linking reduced BMD to endothelial injury and thrombosis. Furthermore, plasma levels of inflammatory and coagulation factors were not measured. Future research should integrate animal models and cellular experiments to elucidate the mechanistic roles of molecules such as osteocalcin and inflammatory cytokines, while supplementing molecular evidence through clinical biomarker assessments to provide a theoretical foundation for developing targeted interventions.

CONCLUSIONS

In summary, reduced femoral neck BMD assessed by CTXA-Hip is an independent risk factor for postoperative DVT in elderly hip fracture patients. When combined with clinical factors such as age, BMI, diabetes, smoking history, and surgical duration, it forms a highly predictive model for DVT risk stratification. This study provides a practical, imaging-based tool for early identification of high-risk patients, supporting individualized prevention strategies.

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