scientific reports

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A comparative study of internal fixation with porous tantalum screws and cannulated screws in the treatment of femoral neck fractures

Dewei Zhao[1,2]✉, Yu Zhang[1,2], Liangliang Cheng[1], Zhijie Ma[1], Feng Wang[1], Xing Qiu[1], Jiawei Ying[1], Tianwei Zhang[1] & Fuyang Wang[1]

Femoral neck fractures (FNF) are a significant concern, particularly in elderly patients with osteoporosis and younger individuals experiencing high-energy traumas. Traditional treatments, like cannulated compression screws (CCSs), often result in complications such as avascular necrosis (AVN). This study evaluated the effectiveness of bidirectional compression porous tantalum screws (BCPTSs) against conventional CCSs in FNF treatment. A retrospective study was conducted on 109 patients with FNF treated at Zhongshan Hospital, Dalian University, from January 2016 to December 2020. Patients were divided into three groups based on the fixation method: two CCSs, three CCSs, and BCPTSs. Postoperative outcomes were assessed using anteroposterior radiographs, with follow-up evaluations at six weeks, three months, 12 months, and 24 months. Diabetic patients were also included as subjects of observation to analyze the association between postoperative osteonecrosis and diabetes. In the two CCSs group, seven patients (7/20, 35%) experienced AVN, compared to 17 patients (17/39, 43.58%) in the three CCSs group. In contrast, only one patient (1/50, 2%) in the BCPTSs group developed nonunion, with no cases of AVN. In a comparison among diabetic patients, there was one case of postoperative AVN in the two CCSs group, five cases in three CCSs group, and one case of fracture nonunion in the BCPTSs group. BCPTSs offer a superior alternative to conventional CCSs in treating FNF, particularly in reducing AVN and nonunion rates. The study highlights the importance of vascular preservation and contributes a new option for treating FNF.

Keywords Femoral neck fracture, Porous tantalum screws, Avascular necrosis, Diabetes

Femoral neck fractures (FNF), a common form of hip fractures, predominantly afflict elderly patients, particularly those suffering from osteoporosis. Nonetheless, these fractures are not exclusive to the geriatric population; they can also result from high-energy traumas in younger individuals[1]. Characterized by a significant rate of reoperation, FNFs pose considerable social and economic challenges[2]. Projections indicate a worrying trend, with the global annual incidence of hip fractures expected to rise by approximately 2.6 million by 2025 and 4.5 million by 2050[3].

The current standard of care for FNF involves surgical intervention. This includes the utilization of cannulated compression screws (CCSs), dynamic hip screws, femoral neck locking compression plates, and, in some cases, joint replacement[4–7]. Although internal fixation using CCSs is a widely adopted surgical method, it is associated with a notable risk of postoperative complications, such as avascular necrosis (AVN) of the femoral head[8,9]. Avascular necrosis, a significant complication following surgical treatment of FNF, demonstrates an incidence ranging from 14.8 to 27% in clinical reports[10,11]. Moreover, Hoshino et al.[12] revealed a notably higher AVN rate of 33% specifically associated with cannulated screws fixation. Nevertheless, surgeons tend to favor internal fixation rather than arthroplasty in young femoral neck fracture patients, internal fixation is less invasive and can preserve the femoral head with better function after healing[13,14].

[1]Department of Orthopaedics, Affiliated Zhongshan Hospital of Dalian University, No 6 Jiefang Street, Zhongshan District, Dalian 116001, Liaoning, China. [2]Dewei Zhao and Yu Zhang contributed equally to this work. ✉email: zhaodewei2016@163.com

In the realm of orthopedic implants, porous tantalum materials have emerged as a superior alternative, offering significant biological and mechanical advantages. Compared to traditional titanium alloys, porous tantalum exhibits a range of beneficial properties, including a lower elastic modulus, higher fatigue strength, and enhanced capability for bone integration. These characteristics make porous tantalum an appealing option for orthopedic reconstruction[15,16], including bone fixation devices, orthopedic implants, vascular stent coatings, and radiographic contrast agents[17,18]. Fernandez et al.[19] implemented porous tantalum rods for treating femoral head avascular necrosis, analysis of retrieved implants demonstrated their exceptional bone ingrowth capacity and osteoconductive properties. However, it is rarely used for internal fixation of femoral neck fractures. Zhao et al.[20] reported a randomized control trial in which 20 patients with femoral neck fractures were treated with porous tantalum screws, demonstrating a significantly lower incidence of postoperative complications compared to those treated with CCSs.

This study aims to critically evaluate the clinical outcomes associated with the use of CCSs and porous tantalum screws in the management of femoral neck fractures. Specifically, it investigates whether porous tantalum screws are more effective in maintaining fracture stability, fostering fracture union, and reducing the incidence of AVN post-surgery.

Materials and methods

Development and design of bidirectional compression porous tantalum screws (BCPTSs)

The porous tantalum screws were prepared adhering to a previously established method and underwent precision machining, resulting in the creation of BCPTSs, a novel addition to orthopedic surgical tools.

The BCPTSs feature a unique design that includes threads at both the anterior and posterior ends, each with a height of 2 mm. The anterior thread pitch is set at 3 mm, contrasting with the posterior thread pitch of 2.5 mm. Central to the screw's architecture is its shaft, measuring 10 mm in diameter, while the overall length of the screw varies between 70 and 110 mm, accommodating various anatomical requirements.

These screws are specifically engineered to exert controlled axial compression, a critical factor in ensuring the stability of the fixation. A noteworthy aspect of the BCPTSs' design is the incorporation of flat bulges in the tail section. This feature significantly facilitates the screws' insertion into the femoral neck, providing robust and secure fixation of FNF as depicted in Fig. 1. This innovative design aims to enhance surgical efficiency while minimizing the risk of complications.

Vascular assessment using digital subtraction angiography (DSA) and novel classification system

In this work, each patient underwent standardized DSA to evaluate vascular integrity around the femoral neck. The data were analyzed using a novel classification system, which correlates fracture displacement with alterations in the blood supply to the femoral head.

Type I Fractures: These are either complete or incomplete fractures with no observable displacement. CT scans in the transverse plane show no discernible displacement or rotation. This category includes all Garden Type I fractures and some Garden Type II fractures. DSA findings indicated no damage to the retinacular arteries in these cases.

Type II Fractures: On coronal CT imaging, these fractures appear well-aligned, but DSA reveals involvement of the anterior retinacular arteries (Type IIa) or the superior retinacular arteries (Type IIb).

Type III Fractures: These are characterized by significant displacement on coronal CT imaging, often accompanied by angular and rotational deformities on transverse CT imaging. DSA examinations allow further categorization into:

Type IIIa: Presence of well-developed inferior retinacular arteries, with the superior and anterior retinacular arteries being compromised. Type IIIb: Well-developed superior retinacular arteries, but with affected inferior and anterior retinacular arteries.

Fig. 1. The external morphology of porous tantalum metal screws.

Type IV Fractures: These fractures display complete displacement on CT imaging, leading to a 'floating' femoral head. DSA imaging shows compromise of the superior, inferior, and anterior retinacular arteries (Fig. 2).

Inclusion criteria and exclusion criteria
Inclusion criteria
The study enrolled patients presenting with Garden type I–III femoral neck fractures who underwent internal fixation surgery. Eligible patients demonstrated good functional mobility prior to injury and had comprehensive postoperative follow-up data available. The minimum follow-up period for inclusion in the study was set at two years.

Exclusion criteria
Patients were excluded from the study if they had pathological fractures or concurrent fractures in other areas of the femur. Additionally, individuals with a follow-up duration of less than two years were not considered for inclusion in the analysis.

Study design and patient cohort
This retrospective study was approved by the Ethical Committee of affiliated Zhongshan Hospital of Dalian University and followed STROBE guidelines and principles. Our research focused on patients with FNF who were admitted to our hospital between January 2016 and December 2020. From the pool of admitted patients, 136 met our predefined inclusion criteria. However, 27 of these patients were subsequently lost to follow-up. Consequently, the study proceeded with a cohort of 109 patients, each having a follow-up period exceeding two years.

For the purpose of this study, patients were stratified into three distinct groups based on the type of internal fixation method employed: 20 patients were treated with two CCSs, 39 with three CCSs, and 50 with BCPTSs. It is noteworthy that all cases involved in this study were classified as closed fractures.

Surgical procedure
All surgical procedures were performed by Dr. Zhao and Dr. Cheng, both of whom are senior surgeons with extensive clinical experience. Each patient underwent general anesthesia or combined block anesthesia, administered either as general anesthesia or a combined nerve block, depending on individual patient requirements. Following anesthesia, patients were positioned supine, with the hip on the affected side elevated approximately 30 degrees to facilitate surgical access. A precise surgical incision, measuring between 2 and 3 cm, was made at the distal end of the greater trochanter. This incision allowed for the careful separation of the vastus lateralis muscle, thereby exposing the proximal femur for subsequent procedures. In the group receiving three CCSs, three 7.3 mm screws were inserted in an inverted triangle configuration, a technique optimized for the fixation of femoral neck fractures. The depth of each screw was meticulously controlled to sit 5 mm below the articular cartilage surface. For patients in the two CCSs group, a pair of screws were placed in parallel alignment. Special attention was paid to ensure that the tips of these screws did not protrude beyond the epiphyseal scar, minimizing potential disruption to the joint. In the group treated with BCPTSs, a single screw was centrally positioned and directed towards the femoral head. Care was taken to ensure that the tip of the tantalum screw did not exceed the boundary of the epiphyseal scar, thereby optimizing fixation while preserving the integrity of the femoral head.

Postoperatively, all patients underwent stages of infection prevention, pain management, anticoagulation, functional training, partial weight-bearing, and gradually progressed to full weight-bearing.

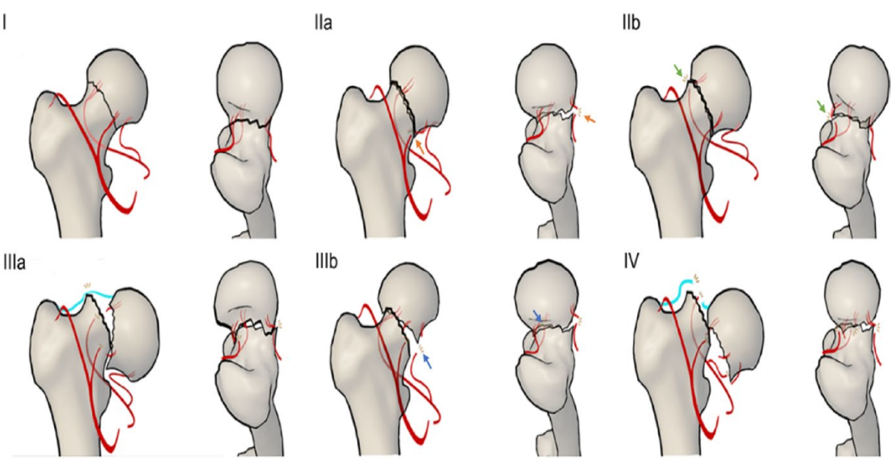

Fig. 2. Vascular Assessment Classification System. The yellow arrow represents the anterior retinacular artery, the green arrow represents the superior retinacular artery, and the blue arrow represents the inferior retinacular artery. Reprinted with permission from Zhao et al.[30].

Evaluation metrics and follow-up assessments

The primary tools for assessing fracture healing and identifying potential complications, such as nonunion and avascular necrosis, were anteroposterior radiographs. These assessments were systematically performed at regular intervals post-surgery: six weeks, three months, 12 months, and 24 months. While radiographic imaging (X-ray examinations) provided the primary means for evaluation, certain cases necessitated the use of computed tomography (CT) or magnetic resonance imaging (MRI) for more detailed analysis. Postoperative follow-up was conducted by Dr. Wang and Dr. Qiu, who assessed fracture union based on established clinical healing criteria, this includes assessing local symptoms, radiological examination to determine if callus formation is present, and whether the patient can walk without crutches for more than three minutes. The assessment of avascular necrosis is based on the Association Research Circulation Osseous (ARCO) staging system[21].

Statistical analysis

The analysis of all collected data was performed using GraphPad Prism, Version 9 (GraphPad Prism Software, Boston, MA, USA). Age was normally distributed and is presented as mean ± standard error of the mean (x ± s). One-way analysis of variance (ANOVA) was used to compare these parameters among the three groups. Other continuous variables were not normally distributed and are reported as median (interquartile range [IQR]); comparisons were made using the Kruskal–Wallis test. Categorical variables are presented as frequencies (percentages), and comparisons among the groups were conducted using the chi-squared test or Fisher's exact test. Statistical significance was set at $P \leq 0.05$.

Results

Characteristics of patients

In this study, a total of 109 patients were analyzed across all groups. Detailed demographic information, including gender, affected side, mechanism of injury, fracture classification, and duration of follow-up, is systematically presented in Table 1. No significant differences were found between the three groups.

Nonunion and avascular necrosis

At the twelve-month follow-up mark, fracture healing was observed in 12 patients from the two CCSs group, 20 patients in the three CCSs group, and 49 patients in the BCPTSs group. At the final follow-up evaluation, the two CCSs group exhibited one case of nonunion (5.0%, 1/20) and seven cases of AVN (35.0%, 7/20). In contrast, the three CCSs group showed two instances of nonunion (5.13%, 2/39) and a higher incidence of AVN (43.58%, 17/39). Notably, the BCPTSs group presented only one case of nonunion (2.0%, 1/50) with no occurrences of AVN. While the rates of nonunion across the three groups did not show significant variation, the lower AVN rate in the BCPTSs group was markedly superior to the other groups, a difference that was statistically significant ($P < 0.001$) as detailed in Table 2.

Group	2 CCSs (n = 20, %)	3 CCSs (n = 39, %)	BCPTSs (n = 50, %)	*P*
Age(year, mean ± SD)	49.00 ± 13.64	53.31 ± 11.11	49.02 ± 13.97	0.479
Gender				0.465
Male	8 (40.00)	20 (51.28)	15 (30.00)	
Female	12 (60.00)	19 (48.72)	35 (70.00)	
Involved side				0.465
Left	10 (50.00)	18 (46.15)	23 (46.00)	
Right	10 (50.00)	21 (53.85)	27 (54.00)	
Injury mechanism				0.471
High energy	2 (10.00)	3 (7.69)	3 (6.00)	
Low energy	18 (90.00)	36 (92.31)	47 (94.00)	
Garden type				0.422
Type I	5 (25.00)	9 (23.08)	16 (32.00)	
Type II	4 (20.00)	13 (33.33)	17 (34.00)	
Type III	11 (55.00)	17 (43.59)	17 (34.00)	
V-E classification				0.397
Type I	6 (30.00)	9 (23.08)	15 (30.00)	
Type IIa	2 (10.00)	9 (23.08)	15 (30.00)	
IIb	1 (5.00)	4 (10.26)	3 (6.00)	
Type IIIa	8 (40.00)	15 (38.46)	14 (28.00)	
IIIb	3 (15.00)	2 (5.12)	3 (6.00)	

Table 1. Demographics and clinical characteristics of patients. Data are mean ± SD, n (%), or median (IQR).

Group	Nonunion (n, %)	AVN (n, %)	Diabetes (n, %)	Diabetes & AVN (n, %)
2 CCSs (n = 20)	1(5.00)	7(35.00)	2(10.00)	1(50.00)
3 CCSs (n = 39)	2(5.13)	17(43.58)	10(25.64)	5(50.00)
BCPTSs (n = 50)	1(2.00)	0(0)	6(12.00)	0(0)
χ^2	0.73	26.65	3.71	4.5
P	0.69	< 0.001	0.16	0.11

Table 2. Comparison of the postoperative complications and primary disease between the three groups. Data are n (%), or median (IQR).

Diabetes and complications

In examining the subset of diabetic patients, one individual in the two CCSs group developed postoperative complications (AVN), compared to five in the three CCSs group (all AVN) and one in the BCPTSs group (fracture nonunion). However, the analysis did not reveal any significant statistical differences in the rate of AVN among diabetic patients across the three groups.

Discussion

The choice of the most effective fixation method for FNF continues to be a widely debated topic in orthopedic surgery. Li et al.[6] have shown that CCSs are associated with a lower rate of AVN compared to dynamic hip screws, though both methods exhibit similar rates of nonunion. When treating younger patients with non-displaced or satisfactorily reduced femoral neck fractures, the prevailing treatment strategy often involves internal fixation via closed reduction using cannulated screws2[22,23]. Further, research by Pauyo et al.[24] and Madhu et al.[25] indicates that the rates of AVN and postoperative nonunion typically range from 20 to 30% and 10 to 33%, respectively. In our study, we observed that among patients treated with two cannulated screws, the postoperative rates of AVN and nonunion stood at 35% and 5%. In contrast, those treated with three screws exhibited rates of 43.58% for AVN and 5.13% for nonunion. Notably, in the cohort of 50 patients treated with BCPTSs and followed for a minimum of two years, only one case of nonunion was reported, with no incidences of AVN. These findings lead us to conclude that the use of tantalum screws in the treatment of Garden type I-III femoral neck fractures results in superior postoperative outcomes and a significantly reduced incidence of complications.

The prevailing etiological theory for traumatic AVN postulates that displacement in FNFs can distort, compress, and even rupture the vasculature supplying the femoral head[26,27]. Nishino et al.[28] have posited that a reduction in blood flow to the femoral head to less than 20% of normal levels is a critical threshold for the onset of osteonecrosis. The vascular architecture around the femoral neck, comprising the superior and inferior retinacular arteries and the branches of the deep femoral circumflex arteries, forms a C-shaped structure critical for femoral head perfusion[29]. Our findings indicate a heightened risk of AVN in the outer upper quadrant of the femoral head when one or two screws are inserted into the upper third of the femoral head (Fig. 3d, h). This risk is attributed to the potential disruption of the arterial network, particularly the superior retinacular artery, leading to compromised blood supply and subsequent necrosis of the femoral head. To address this challenge, our study introduced a novel classification system for assessing vascular injuries[30]. This system enables a more comprehensive evaluation of the extent of vascular damage around the femoral neck, thereby informing the development of targeted treatment strategies aimed at minimizing the risk of nonunion and AVN. Levack et al.[31] also suggested that reduced arterial inflow and venous outflow may lead to AVN of the femoral head, although this process usually takes time to develop. This may help explain why early bone healing in this study showed no significant difference, while the incidence of late-stage osteonecrosis was clearly higher.

Porous metallic implants, derived from various sources, are renowned for their adjustable mechanical properties. A key feature of these implants is their porous structure, which not only reduces the elastic modulus but also mitigates the stress shielding effect, thereby promoting bone ingrowth and expediting bone integration[32,33]. Tantalum, identified in 1802 by the Swedish chemist Ekeberg as an allotrope of niobium, is particularly notable in this context. Its derivative, porous tantalum, has garnered significant attention for its unique structural properties that mimic cancellous bone, notably its elastic modulus and porosity[34]. A comparative study by Wauthle et al.[35] evaluated the mechanical properties of porous tantalum against those of commercial pure titanium and Ti6Al4V. This study highlighted the superior static loading strength of Ti6Al4V. However, despite the comparable dynamic and static compression properties shared between porous tantalum and titanium, porous tantalum demonstrates enhanced fatigue strength, microhardness, and tensile strength. These attributes position porous tantalum as a more favorable material for clinical applications, particularly in orthopedic and dental implants[36]. Ma et al.[16] conducted comprehensive in vitro and in vivo investigations on porous tantalum scaffolds and found that, compared to titanium alloys, porous tantalum significantly enhanced the proliferation, migration, and osteogenic differentiation of mesenchymal stem cells. Additionally, in a load-bearing goat femoral neck fracture model, fixation with porous tantalum screws demonstrated excellent osseointegration and its potential for clinical application in orthopedic implants. A prospective controlled study by Zhao et al.[20] found that in the treatment of Garden I–III femoral neck fractures with CCSs, the postoperative rates of AVN and nonunion were 19.05% and 4.76%, respectively. In contrast, no cases of AVN or nonunion were observed in the BCPTSs group. Furthermore, finite element analysis showed that fracture displacement after tantalum screw fixation was less than 0.5 mm, with stress primarily concentrated at the distal end of the femur (26.58 MPa). Wang et al.[37] evaluated the biomechanical performance of BCPTS using finite element analysis.

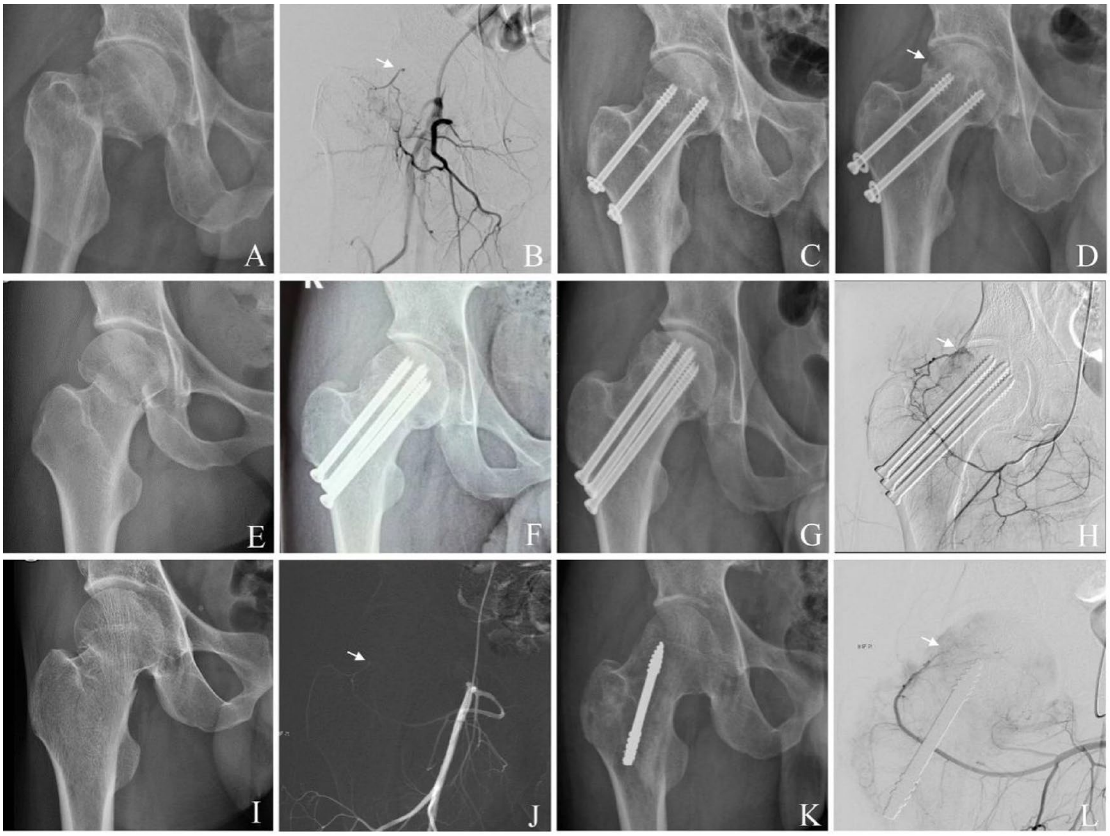

Fig. 3. Case 1. (**A**) A patient with a Garden III type femoral neck fracture. (**B**) Preoperative DSA showed thickening and interruption of the superior supporting artery supply entering the femoral head. (**C**) The fracture was fixed with two cannulated screws. (**D**) At the 6-month postoperative X-ray examination, ischemic necrosis changes were observed in the upper outer portion of the femoral head. Case 2. (**E–F**) A patient with a Garden II type femoral neck fracture, fixed with three cannulated screws. (**G**) At 7 months postoperative, X-ray revealed ischemic necrosis and collapse in the weight-bearing area of the femoral head. (**H**) DSA indicated that the superior supporting artery supply did not extend to the bone area within the screw implantation zone. Case 3. (**I**) A patient with a Garden I type femoral neck fracture. (**J**) Preoperative DSA revealed disruption of the superior supporting artery supply at the head-neck junction. (**K**) The fracture was fixed with a single porous tantalum metal screw, ensuring the distal end did not surpass the epiphyseal line. (**L**) At 26 months postoperative follow-up, good fracture healing was observed, and DSA demonstrated that the superior supporting artery supply entered the femoral head through the epiphyseal line.

The results showed that a single porous tantalum screw provided a maximum implant stress of 126.8 MPa and an interfragmentary motion of 0.31 mm, which was comparable to that of two cannulated screws. However, its design requires fewer screws, maintaining sufficient mechanical strength while minimizing the risk of vascular disruption, thus offering a novel option for stable femoral neck fractures.

The use of three CCSs is a prevalent method for the internal fixation of femoral neck fractures[38]. However, conventional cannulated screw fixation presents several challenges. Notably, the depth of screw placement and the potential instability of the guide during the drilling process can lead to vascular and bone injuries due to repeated drilling. Moreover, this technique may disrupt the vascular supply to the femoral head's epiphyseal arterial network, a complication we have previously reported[30]. Achieving optimal screw placement during surgery is complex, and incorrect positioning of the posterior screw risks damaging the deep medial femoral circumflex artery, an integral component of the superior retinacular artery system. The superior retinacular artery is critical as it serves as the primary or terminal blood supply to the superior part of the femoral head. These issues can indirectly lead to various postoperative complications, including nonunion, AVN, and failure of internal fixation[39]. In contrast, the BCPTSs we have developed offer a solution to these challenges. They provide central fixation, which helps stabilize the fracture while minimizing the risk of damaging the superior and inferior retinacular arteries during insertion. The insertion depth of BCPTSs is carefully controlled to avoid surpassing the epiphyseal scar of the femoral head, thereby protecting the epiphyseal arterial network (Fig. 3).

In our vascular assessment classification system for femoral neck fractures, cases classified as Type I-III generally indicate the preservation of at least one retinacular artery. The use of BCPTSs in these cases plays a pivotal role. BCPTSs facilitate anatomical reduction of the fracture, which can contribute to the restoration of partial blood supply to the affected area. This method of fixation is specifically designed to maximize the preservation of vascular integrity, both in the region surrounding the femoral neck and within the femoral head itself. For patients with fractures classified as Type IV, where the vascular compromise is more extensive, a more complex approach is required. In these situations, we typically employ a combination of strategies, including internal fixation complemented by vascularized bone grafting or joint replacement, depending on the patient's age and overall health condition. Such an approach is tailored to address the significant vascular damage and ensure optimal recovery and rehabilitation outcomes.

Diabetes mellitus, known for its detrimental effects on both large and small blood vessels[40], has been identified as a significant risk factor for the development of AVN[41–43]. The disease's pathogenic mechanisms can adversely affect bone health, potentially impairing bone formation, accelerating apoptosis in bone cells, and hindering the formation of new micro-vessels[44]. Our study's findings reveal a notable correlation between diabetes and postoperative complications in FNFs. Specifically, diabetic patients with FNF undergoing treatment with CCSs exhibited a 50% likelihood of developing postoperative femoral head necrosis (Table 2). Complementary to our findings, research conducted by Lai et al.[34] demonstrates that diabetic individuals face a 1.16-fold increased risk of AVN compared to their non-diabetic counterparts. These insights underscore the critical role of diabetes as a high-risk factor for compromising femoral head blood flow, subsequently leading to traumatic osteonecrosis. The recognition of diabetes as a significant contributory factor in AVN incidence necessitates careful consideration in the management of FNF, particularly in diabetic patients.

This research, while providing valuable insights, is subject to certain limitations that must be acknowledged. Primarily, the study is based on Level IV evidence, comprising retrospective case series. Consequently, it lacks the robustness of prospective randomized controlled trials, which would offer higher-quality Level I/II evidence. In addition, here is no matching or statistical adjustment was performed between groups for variables such as age, fracture type, and diabetes, which may potentially influence the incidence of complications. Moreover, a notable constraint in our study was the insufficient number of DSA results obtained during the postoperative follow-up period. This shortfall hindered our ability to thoroughly assess and compare the preservation of femoral intraosseous blood flow across different fixation methods. Such comparative analysis is crucial for understanding the vascular implications of each surgical technique and could significantly contribute to the optimization of treatment strategies for femoral neck fractures.

Conclusion

This study highlights significant advancements in the treatment of FNF with a particular focus on the use of BCPTSs. Our results indicate that, compared to CCSs, BCPTSs are more suitable for patients with Garden classification types I–III of femoral neck fractures, demonstrating significant advantages particularly in reducing the risks of AVN and nonunion. Additionally, the study underlines the importance of considering diabetes mellitus as a high-risk factor for postoperative complications, particularly AVN. The data indicate that diabetic patients are more susceptible to femoral head necrosis following FNF treatment, necessitating a more tailored approach in their management.

Data availability

The dataset used and analysed during the current study is available from the corresponding author on reasonable request.

Received: 22 May 2024; Accepted: 26 May 2025
Published online: 04 June 2025

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Author contributions
Dewei Zhao: Corresponsing author: Concept development, actual surgery. Yu Zhang: manuscript writing, data analysis. Liangliang Cheng: review and editing. Jiawei Ying and Tianwei Zhang: data collection. Zhijie Ma: resources. Feng Wang and Xing Qiu: data analysis and curation. Fuyang Wang: validation.

Funding
The article was funded by National Natural Science Foundation of China (Grant No. 82172398), Dalian Key Medical Specialty Construction Fund Project "Peak Climbing" Program (Grant No. 2021-243).

Declarations

Competing interests
The authors declare no competing interests.

Ethical approval
This study was in accordance with Helsinki principles. Signed informed consent was obtained from the participant.

Additional information
Correspondence and requests for materials should be addressed to D.Z.

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