Orthopaedic Surgery

CLINICAL ARTICLE

Medial Buttress Plate and Allograft Bone-Assisted Cannulated Screw Fixation for Unstable Femoral Neck Fracture with Posteromedial Comminution: A Retrospective Controlled Study

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Objective: To investigate the outcomes of open reduction and internal fixation combined with medial buttress plate (MBP) and allograft bone-assisted cannulated screw (CS) fixation for patients with unstable femoral neck fracture with comminuted posteromedial cortex.

Methods: In a retrospective study of patients operated on for unstable femoral neck fractures with comminuted posteromedial cortex from March 2016 to August 2020, the clinical and radiographic outcomes of 48 patients treated with CS + MBP were compared with the outcomes of 54 patients treated with CS only. All patients in the CS + MBP group were fixed by three CS and MBP (one-third tubular plates or reconstructive plates) with bone allografts. The surgery-related outcomes and complications were evaluated, including operative time, blood loss, union time, femoral head necrosis, femoral neck shortening, and other complications after the operation. The Harris score was evaluated at 12 months after the operation.

Results: All patients were followed up for 12–40 months. The average age of patients in the CS-only group (54 cases, 22 females) and CS + MBP group (48 cases, 20 females) was 48.46 ± 7.26 and 48.73 ± 6.38 years, respectively. More intraoperative blood loss was observed in the CS + MBP group than that of patients in CS-only group (153.45 ± 64.27 *vs* 21.86 ± 18.19 ml, $t = 4.058$, $P = 0.015$). The average operative time for patients in the CS + MBP group (75.35 ± 27.67 min) was almost double than that of patients in the CS-only group (36.87 ± 15.39 min) ($t = 2.455$, $P < 0.001$). The Garden alignment index of patients treated by CS + MBP from type I to type IV was 79%, 19%, 2%, and 0%, respectively. On the contrary, they were 31%, 43%, 24% and 2% for those in the CS-only group, respectively. The average healing times for the CS-only and CS + MBP groups were 4.34 ± 1.46 and 3.65 ± 1.85 months ($t = 1.650$, $P = 0.102$), respectively. Femoral neck shortening was better in the CS + MBP group (1.40 ± 1.73 mm, 9/19) than that in the CS-only group (4.33 ± 3.32 mm, 24/44). Significantly higher hip function was found in the CS + MBP group (85.60 ± 4.36 *vs* 82.47 ± 6.33, $t = 1.899$, $P = 0.06$). There was no statistical difference between femoral head necrosis (4% *vs* 11%, $\chi^2 = 1.695$, $P = 0.193$) and nonunion (6% *vs* 9%, $\chi^2 = 0.318$, $P = 0.719$).

Conclusion: For unstable femoral neck fractures with comminuted posteromedial cortex, additional MBP combined with bone allografts showed better reduction quality and neck length control than CS fixation only, with longer operative time and more blood loss.

Key words: Bone allograft; Cannulated screws; Femoral neck fractures; Medial buttress plate; Posteromedial defect

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Introduction

The femoral neck fracture is frequently caused by high-energy trauma in the young population[1–3]. As reported, a high necrosis rate of 10%–43% was observed even though a rough satisfactory reduction was achieved[4,5]. A meta-analysis reported a malunion rate of 7.1%, implant failure rate of 9.7%, and reoperation rate of 20% for displaced femoral neck fractures[6]. In another study with a median follow-up of 8 years, 14% of the cohort was converted to total hip arthroplasty[7]. Less avascular necrosis and nonunion are important goals in the management of femoral neck fracture. A primary determinant was reported to be the anatomic reduction with stable fixation[8]. Implants with angle stability are the preferred choice[9,10]. In a study comparing cannulated screw (CS) or sliding hip screw fixation, more failures were observed for those treated by CS (21% *vs* 3%) within 6 months[11]. Biomechanical analyses indicated that under static loading, dynamic hip screw with anti-rotation screws produced lower femoral head displacement and inter-fragmentary movement than CS[12].

Another challenging problem in young patients with femoral neck fracture is the posterior comminution caused by serious trauma[5,13]. In a study including young patients with vertical femoral neck fractures, major comminution (>1.5 cm) was noticed in the inferior (94%) and posterior (82%) quadrants of the femoral neck[14]. Without the support of the posterior femoral neck cortex, these femoral necks may be unstable as expected after screw fixation, which had been confirmed in a biomechanical test[15]. More neck shortening (18.2% *vs* 28.9%), avascular necrosis (15.3% *vs* 34.2%), and conversion to hip arthroplasty (18.2% *vs* 50.0%) were reported in patients with displaced femoral neck fractures and posterior comminuted cortex who were fixed with inverted parallel CS, in comparison with those without posterior comminution[16].

To improve the stability of femoral neck fracture with posterior comminution, the medial buttress plate (MBP) was used, and promising outcomes were reported[17,18]. Initially, the MBP fixation was introduced in the management of vertical femoral neck fractures in young adults to resist shearing forces and to reduce the high rate of complications[18]. Later, combining three CSs and MBP using a direct anterior approach, union without femoral neck shortening was achieved in 89% of 27 young Pauwels III fractures[19]. Satisfactory outcomes were also observed in another study of irreducible displaced femoral neck fractures in young patients[20]. In a recent meta-analysis, patients with extra medial femoral plate support showed shorter healing time, less complications, and higher Harris scores[21].

Bone grafts such as vascularized greater trochanter bone grafts[22], quadratus femoris muscle pedicle bone grafts[23], free vascularized fibular grafts[24], vascularized iliac grafts[25], and deep circumflex iliac artery-bone grafts[26] have been used to treat young femoral neck fractures. Significantly lower nonunion and avascular necrosis were observed. However, longer operative time, more blood loss, and wound complications were major disadvantages. Advancements in allografts in past decades have made them a favorable alternative due to their convenience, abundance, and lack of related morbidity[27].

In our trauma center, the application of MBP and allograft bone was scheduled to treat young patients with unstable femoral neck fracture and comminuted posteromedial cortex since March 2016. The current study retrospectively summarized patients with unstable femoral neck fracture and comminuted posteromedial cortex who were treated with CS-only or a combination of CS, MBP, and allograft bone (CS + MBP), by which we tried to (i) improve the reduction and stability in Pauwels III femoral neck fractures to provide promising healing and hip function outcomes and (ii) to illustrate the surgical tips for application of MBP.

Materials and Methods

Inclusion and Exclusion Criteria

The inclusion criteria were as follows: (i) patients with unstable femoral neck fracture, Garden III or IV (Pauwels III); (ii) posterior comminution of the femoral neck confirmed by CT scan; (iii) patient age from 18 to 65 years; (iv) patients treated by CS-only or CS + MBP; (v) follow-up time longer than 12 months; and (vi) clinical and radiological outcomes were available. Patients were excluded according to the following rules: (i) previous hip deformation or surgery; (ii) patients with serious osteoporosis or pathological fracture; and (iii) those with serious medical and mental problems.

Included Patients

The medical records of unstable femoral neck fractures with comminuted posteromedial cortex treated at Chenggong Hospital Affiliated to Xiamen University from March 2016 to August 2020 were retrospectively analyzed. X-ray and CT scans were performed to confirm Pauwels III fractures and the existence of posterior comminution or defects. All patients had fresh Pauwels III-type femoral neck fractures with posteromedial femoral neck comminution. All patients underwent reduction and internal fixation with three CSs. An extra MBP and bone allograft were added starting in March 2016. Informed consent was obtained from all patients before the operation. The current study was approved by the Ethics Committee of Xiamen University Affiliated Chenggong Hospital (20160103).

Surgery Procedures

Preoperative Preparations

All patients received skin traction by 2 kg after registration. Regular imaging and clinical examinations were performed. Abnormal tests were treated to normal range. Low molecular weight heparin (6 kD per day) and a lower extremity venous pump were used to prevent deep venous thrombosis in lower extremities.

Intraoperative Procedures

All patients were offered lumbar epidural anesthesia or general anesthesia based on personal medical conditions. The patient was supine on a fluoroscopic operating table. For patients in the CS-only group, closed reduction was performed under fluoroscopy. The fracture was fixed as a regular procedure with three 7.3-mm CSs in inverted triangles. For patients in the CS + MBP group, a longitudinal incision of 6–8 cm was made in front of the hip joint, extending distally from 2.0 cm below the anterior superior iliac spine. Exposure was performed between the tensor fascia lata and sartorius followed by separation between the deep fascia along the medial edge of the tensor fascia lata and reaching the joint capsule through the gap between the gluteus medius and rectus femoris. Open reduction was achieved and fixed by three 7.3-mm CSs in inverted triangles and confirmed by C-arm fluoroscopy. After gentle flexion of the hip and external rotation of the injured low limb, the buttress plate (1/3 tubular plates or reconstructive plates) was contoured and fixed on the medial femoral cortices. The allogeneic cancellous bone was packed into the defect of the femoral neck after reduction. After it was checked again by C-arm fluoroscopy, the wound was sutured layer by layer. The extra exposure of femoral neck fracture and fixation by MBP is illustrated in Figure 1.

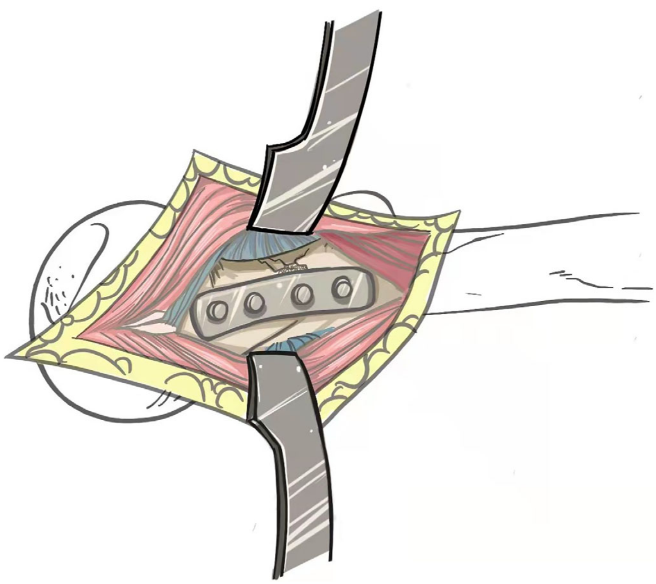

Fig. 1 The illustration of extra exposure of femoral neck fracture and fixation by medial buttress plate. The femoral neck fracture was exposed through an anterior approach of the hip joint. A pre-contoured plate was fixed against the medial cortex while the allogeneic cancellous bone was packed into the defect of the femoral neck after reduction

Postoperative Management

Isometric quadriceps muscle exercise training and ankle flexion and extension were recommended when patients could tolerate pain. After postoperative care for 3–5 days, patients were discharged. Non-weight ambulation was allowed when patients could endure pain. Partial and full weight was allowed when partial or full trabecular bridge was confirmed by X-ray test. Patients were followed up regularly at 1, 2, 3, 6, 12, 24, and 36 months after surgery with anteroposterior hip X-ray and CT scans when necessary. Hip function was evaluated.

Data Collection and Outcome Measures

Surgery-Related Outcomes

The primary procedure-related outcomes in the current study included operative time, intraoperative bleeding, and fluoroscopy times. The time of surgery was recorded from the beginning of skin incision until surgical closure, which could reflect the proficiency of the operators for these two different techniques and the risk of infection. The intraoperative bleeding was recorded by weighing the different pre- and post-operative sterile gauzes used during operation on digital electronic scales. It revealed the blood loss caused by two different kinds of exposure for fixation.

Imaging Evaluations

The reduction quality was evaluated by anteroposterior and lateral hip X-rays according to the Garden index. The time of bony healing was recorded. Nonunion was defined as a fracture that had not healed for at least 6 months after fracture and had no tendency to heal further for 3 months. Femoral neck shortening was evaluated using the method detailed by Zlowodzki *et al.*[28]. The most recent anteroposterior radiograph of the fractured hip was compared with the contralateral uninjured hip by overlapping with a reference of the diameters of screws. The Chinese guidelines for osteonecrosis of the femoral head in adults were used to measure avascular necrosis[29].

Harris Score

The Harris hip score (HHS) was used to evaluate the patient's hip function[30]. The HHS system mainly includes pain, function, deformity, and range of motion. The score standard had a maximum of 100 points (best possible outcome), and it was classified into excellent >90 points, good 80–90 points, moderate 70–79 points, and poor <70 points.

Statistical Analysis

Clinical and radiological outcomes were compared between patients in the CS-only group an CS + MBP group.

Continuous variables, such as operative time, blood loss, healing time, and Harris score, were described as the mean ± standard deviation. The differences between continuous variates were compared using Student's *t*-test. The other categorical data were presented as the number and percentage (*N*, %). They were compared by the χ^2 test or Fisher's exact test. $P < 0.05$ was considered as statistically significant. All statistical analyses were performed using SPSS 22.0 (IBM Corporation, Armonk, NY).

Results

General Results

According to the inclusion criteria, 48 patients treated by CS + MBP and 54 patients treated by CS only were included for retrospective analysis. All patients were followed up from 12 to 40 months. Age, sex, and bone mass index were comparable between the two groups, as shown in Table 1.

Intraoperative Outcomes

More intraoperative blood loss was observed in the CS + MBP group (153.45 ± 64.27 ml) than in the CS-only group (21.86 ± 18.19 ml), ($t = 4.058$, $P < 0.001$). A longer operative time was seen for patients in the CS + MBP group (75.35 ± 27.67 min) than for those in the CS-only group (36.87 ± 15.39 min), ($t = 2.455$, $P = 0.015$). According to the Garden alignment index, there were 38, nine, one, and zero type I, II, III, and IV cases in the CS + MBP group and 17, 23, 13, and one case in the CS-only group, respectively.

For patients treated by extra MBP, significant defect was noticed at the posterior or inferior femoral neck after regular reduction. The average distance of cortex on the line of femoral neck was 14 ± 3 mm. After further reduction and being fixed by MBP, the defect was cleaned and impacted by allograft bone. With meticulous manipulation, no significant damage of important vascular and nervous structure was noticed for all patients.

Clinical Characteristics

With an average follow-up of 17.3 months, the excellent, good, medium, and poor Harris scores were 17, 26, 4, and 1, respectively, in the CS + MBP group. Better alignment was noticed in patients the CS + MBP group ($\chi^2 = 25.163$, $P < 0.001$). The healing time, hospital stay, and other detailed clinical information are summarized in Table 1.

Radiographical Appearance

Based on regular radiological examination, the average healing times for the CS-only and CS + MBP groups were 4.34 ± 1.46 and 3.65 ± 1.85 months ($t = 1.650$, $P = 0.102$), respectively. A typical case treated by a CS + MBP is illustrated in Figure 2. A typical case treated with CS-only is shown in Figure 3. No hip impingement was noticed in patients treated with extra MBP.

TABLE 1 Basic information of patients and perioperative characteristics between the CS-only and CS + MBP group

Basic information	CS + MBP	CS-only	*t* or χ^2	*P* Value
Gender (male/female)	28/20	32/22	0.009	0.924
Age (years)	48.73 ± 6.38	48.46 ± 7.26	0.054	0.957
BMI (kg/m^2)	23.57 ± 3.43	23.92 ± 4.25	−0.372	0.711
Operation time (min)	75.35 ± 27.67	36.87 ± 15.39	2.455	0.015
Blood loss (ml)	153.45 ± 64.27	21.86 ± 18.19	4.058	< 0.001
Fluoroscopy time (min)	15.25 ± 5.38	21.86 ± 7.54	1.368	0.174
Hospital stays (d)	6.23 ± 2.38	5.16 ± 1.45	0.771	0.442
Healing time (months)	3.65 ± 1.85	4.34 ± 1.46	1.650	0.102
Garden alignment index				
I	38 (79%)	17 (31%)	25.163	< 0.001
II	9 (19%)	23 (43%)		
III	1 (2%)	13 (24%)		
IV	0 (0%)	1 (2%)		
Postoperative Harris score	85.60 ± 4.36	82.47 ± 6.33	1.899	0.060
Excellent	17 (35%)	16 (30%)	4.878	0.192
Good	26 (54%)	23 (43%)		
Medium	4 (8%)	12 (22%)		
Poor	1 (2%)	3 (6%)		
Neck shortening (mm)	1.40 ± 1.73	4.33 ± 3.32	3.079	0.003
≤5	5 (10%)	13 (24%)	9.227	0.020
5–10	4 (8%)	7 (13%)		
≥10	0 (0%)	4 (7%)		
Non-union	3 (6.3%)	5 (9.3%)	0.318	0.719
Necrosis	2 (4.2%)	6 (11.1%)	1.695	0.193

Abbreviations: CS, cannulated screw; MBP, medial buttress plate.

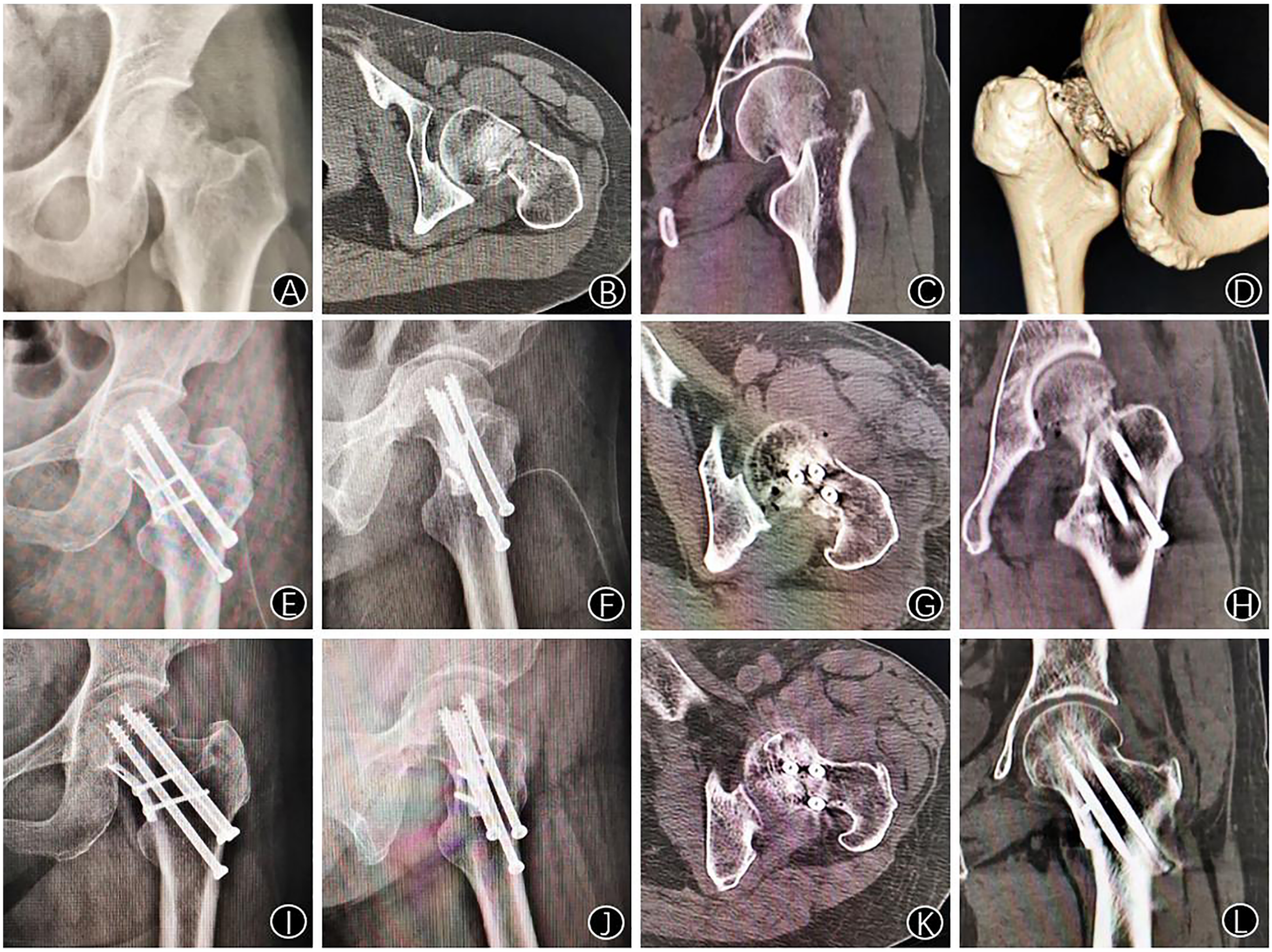

Fig. 2 A 48-year-old female patient with left femoral neck fracture who was treated by cannulated screw (CS), medial buttress plate (MBP), and bone allograft. (A) Preoperative radiographs suggested a fracture of the left femoral neck (Garden III type, Pauwels III type); (B–D) preoperative CT examination revealed comminuted posteromedial cortex; (E–H) the patient was treated with CS, MBP, and bone allograft. Excellent reduction was achieved; (I–L) the X-rays examination and CT scan after 5 months postoperative follow-up showed fracture healing, no femoral neck shortening, and no implant failure

Complications

Three patients in the CS + MBP group and five patients in the CS-only group showed nonunion of the femoral neck. All these non-unions were treated by implant removal and regular follow-up. One out of three non-unions in the CS-MBP group and two cases in the CS-only group healed in late follow-up. The others progressed to femoral head necrosis. Femoral head necrosis was observed in two patients in the CS + MBP group and six patients in the CS-only group. All cases with necrosis of the femoral head were treated by total hip arthroplasty. Femoral neck shortening was observed in nine (19%) patients in the CS + MBP group and 24 (44%) patients in the CS-only group ($\chi^2 = 9.227$, $P = 0.020$). There was no statistical difference in non-union and necrosis between the two groups (Table 1).

Discussion

Due to the injury mechanism caused by high-energy trauma, femoral neck fractures in the young population are always displaced[1–3]. Posterior comminution is also commonly noticed in young femoral neck fractures[5,13]. Collinge *et al.* reported that the vertical fracture averaged 60° and axial fracture obliquity averaged 24°, with major femoral neck comminution (>1.5 cm) in 82% of posterior quadrants[14]. The shear force from vertical fracture and weak support of the posterior femoral neck

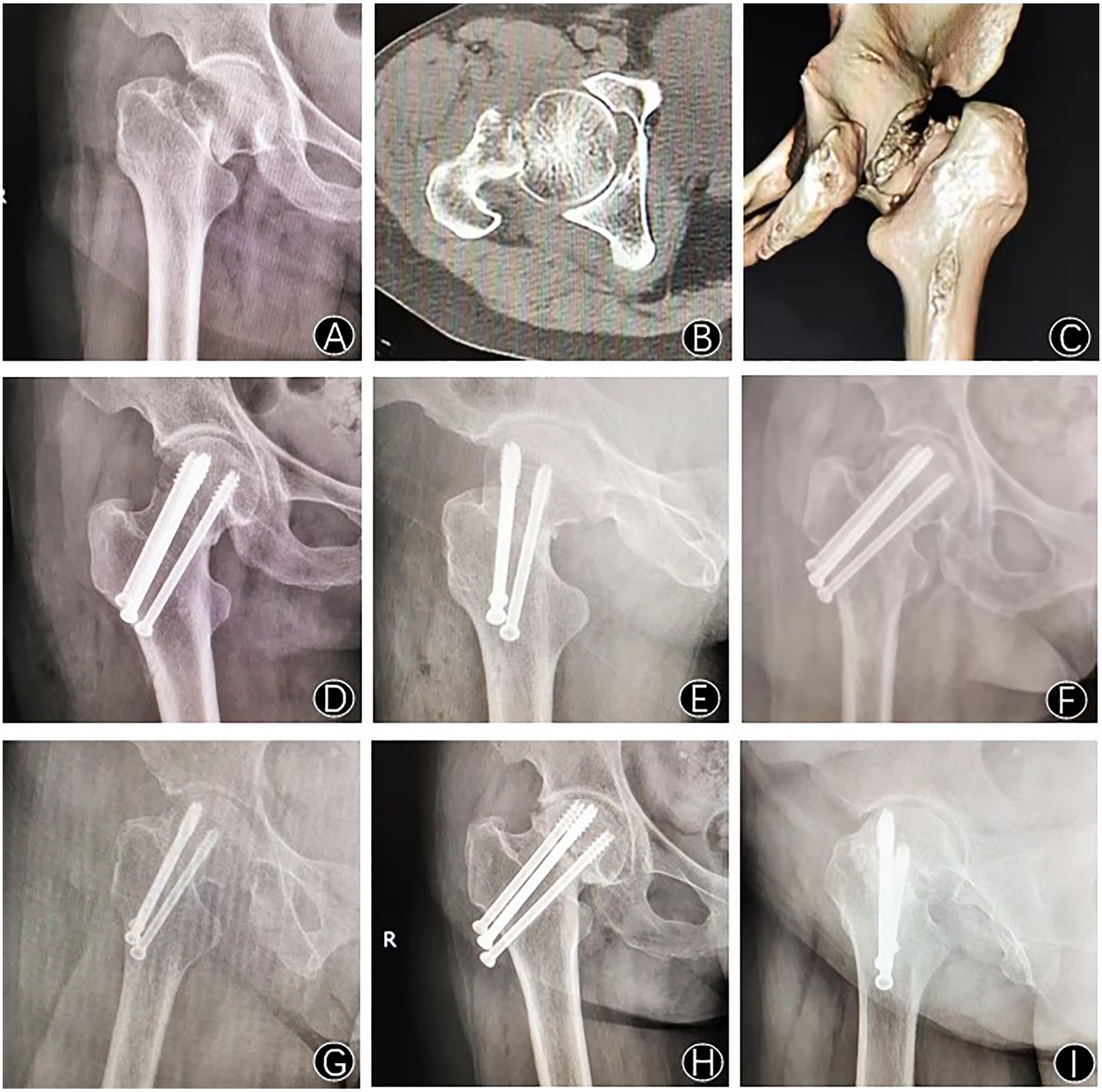

Fig. 3 A 52-year-old female with Pauwels III femoral neck fracture who was treated by cannulated screw only. (A) Preoperative anterio-posterior radiograph; (B–C) preoperative CT, bone defect was noticed in posterior femur; (D–E) the patient was closely reduced and fixed by three screws; (F–G) Three months postoperatively, delay healing and screw withdraw was noticed; (H–I) Ten months postoperatively, the fracture did not heal and shortening of femoral neck and screw cutout were noticed

cortex cause instability after regular fixation, leading to a higher risk of fracture nonunion and avascular necrosis. In the current study, satisfactory outcomes were achieved by the combination of CS + MBP and bone allografts in the treatment of Pauwels III femoral neck fractures with comminuted posteromedial cortex. Favorable outcomes were achieved compared with traditional inversed CS fixation.

Robust Stability by MBP Guarantee Less Complication and Better Function

To ensure better healing after fracture, one important principle to consider is excellent reduction and stable fixation. In a study of approximately 250 patients with femoral neck fracture, 16% of cases had necrosis of the femoral head, and the multivariate analysis revealed that displaced type and dissatisfied reduction were independent risk factors affecting femoral head necrosis[31]. In this study, femoral neck fracture was directly reduced to guarantee high reduction quality. Extra use of MBP provided protection to avoid possible displacement during postoperative rehabilitation. In a recent study, 34 out of 110 (31%) femoral neck fractures showed negative buttress position reduction, with the distal fracture segment located superiorly medially to the lower-lateral part of the proximal fracture segment[32]. Compared with 14.6% of patients with anatomic reduction, 38.2% of patients with negative buttress position reduction showed complications, and 29.4% received reoperation. The MBP can clamp the fracture apex into position and eliminate the risk of further dislocation, which was a possible reason for gaining better results. This issue is extremely important for patients with local comminution.

Enough stability by fixation is another important factor influencing fracture healing. The shear force of Pauwels type III fractures is a significant danger for screw fixation, especially for young populations who are more active after surgery. More robust fixation methods should be performed for these populations. In comparison with fixation by ordinary CS, transverse cancellous lag screw[33], sliding hip screw fixation[11], and dynamic hip screws with anti-rotation screw[12] improved the stability of fixation and achieved better clinical outcomes. These methods indirectly provided extra stability from the lateral side of the femur. The medial plate can directly improve stability from the medial side of the femur[17,18]. The biomechanical test[34] and finite element analysis[35] confirmed that the addition of a medial plate achieved superior buttress stability. Just like our study, the medial plate provided extra buttress support, which can provide more stability in combination with screws in the center of femoral neck. The negative shared force between fracture fragments was transferred to a positive compression force, which can contribute to healing[18]. Based on these findings, all patients in the CS-MBP group were allowed partial and full weight bearing earlier than those in CS-only group. They were also more confident during the rehabilitation. Thus, femoral neck shortening was less common in the CS + MBP group in the current study than in the group treated with CS.

Local comminution or defects after reduction caused instability for fixation, which was disadvantageous for healing. In addition, it can also interfere with the healing progress from the perspective of blood support and structure continuity. Thus, the bone graft is a good choice to address posterior comminution and defects after reduction to improve healing and to avoid avascular necrosis. Vascularized greater trochanter bone grafts, quadratus femoris muscle pedicle bone grafts, fibular grafts, and iliac grafts have been tried previously. Extra incision, longer operative time, and more blood loss were major disadvantages. Complex procedures and long learning curves also limit the application of these grafts. Advancements in allografts in past decades have made them a favorable alternative due to their convenience, abundance, and lack of related morbidity[27]. In the current study, we used allogeneic bone to pack the space between the medial plate and fracture, which may be another contributing factor for better results.

Surgical Tips for Application of MBP

Several points should be considered when the MBP is used. Based on the basic principles of buttress plates and the anatomic features of the proximate femur, the medial plate is not suitable for subhead-type fractures. The prominent plate tip may cause hip impingement and local pain. The support plate is most suitable for transcervical femoral neck fracture. When placing the plate, the plate, such as a one third tubular plate or thin reconstructive plate, should be shaped easily to fit the anatomy of the proximate femur. A new design should be tried to gain stronger support power and thinner shape. The length and angle of fixed screws should be carefully planned to avoid interference with the CS. The related arteries in the incision should be meticulously protected during exposure, reduction, and internal fixation, thus avoiding any decrease in local blood support. According to anatomic research, the MBP should be positioned at 6:00 along the femoral neck, which cannot endanger the blood supply of the femoral head[36]. As a previous study reported, the use of a medial plate caused a longer operative time and more blood loss[21]. Careful exposure and hemostasis should be scheduled throughout the procedures to reduce blood loss and to avoid unnecessary wound complications.

Limitations

Several limitations should be stated. The study analyzed 48 unstable femoral neck fractures treated with a combination of CS and MBP. The sample size was not prospectively calculated, and the follow-up was not long enough to observe some complications, especially avascular necrosis of the femoral head. The accurate incidence of necrosis should be recorded in the future after long-term follow-up in a large cohort. The retrospective design had a high risk of bias in patient selection and measurements. The actual effect of the combination of CS, MBP, and bone allografts in the treatment of unstable femoral neck fracture with comminuted posteromedial cortex should be further evaluated in randomized or prospective studies. The weaknesses of longer operative time and more blood loss were also resolved by more practice and careful surgery. Besides, the need of an additional approach for plating and potential surgical difficulty for plate removal should be addressed by long-term practice.

Conclusion

For unstable femoral neck fractures with comminuted posteromedial cortex, the combination of three CSs, MBP, and bone allografts were an effective choice to gain earlier weight bearing, faster fracture healing, and better hip function.

Conflict of Interest

All authors declare that they have no conflicts of interest.

References

1. Lifeso R, Younge D. The neglected hip fracture. J Orthop Trauma. 1990;4:287–92.
2. Leung PC, Shen WY. Fracture of the femoral neck in younger adults. A new method of treatment for delayed and nonunions. Clin Orthop Relat Res. 1993;295:156–60.
3. Robinson CM, Court-Brown CM, McQueen MM, Christie J. Hip fractures in adults younger than 50years of age. Epidemiology and results. Clin Orthop Relat Res. 1995;312:238–46.
4. Dedrick DK, Mackenzie JR, Burney RE. Complications of femoral neck fracture in young adults. J Trauma. 1986;26:932–7.
5. Swiontkowski MF, Winquist RA, Hansen ST Jr. Fractures of the femoral neck in patients between the ages of twelve and forty-nine years. J Bone Joint Surg Am. 1984;66:837–46.
6. Slobogean GP, Sprague SA, Scott T, Bhandari M. Complications following young femoral neck fractures. Injury. 2015;46:484–91.
7. Stockton DJ, O'Hara LM, O'Hara NN, Lefaivre KA, O'Brien PJ, Slobogean GP. High rate of reoperation and conversion to total hip arthroplasty after internal fixation of young femoral neck fractures: a population-based study of 796 patients. Acta Orthop. 2019;90:21–5.
8. Stacey SC, Renninger CH, Hak D, Mauffrey C. Tips and tricks for ORIF of displaced femoral neck fractures in the young adult patient. Eur J Orthop Surg Traumatol. 2016;26:355–63.
9. Hoshino CM, Christian MW, O'Toole RV, Manson TT. Fixation of displaced femoral neck fractures in young adults: fixed-angle devices or Pauwel screws? Injury. 2016;47:1676–84.
10. Sprague S, Slobogean GP, Scott T, Chahal M, Bhandari M. Young femoral neck fractures: are we measuring outcomes that matter. Injury. 2015;46:507–14.
11. Gardner S, Weaver MJ, Jerabek S, Rodriguez E, Vrahas M, Harris M. Predictors of early failure in young patients with displaced femoral neck fractures. J Orthop. 2015;12:75–80.
12. Samsami S, Saberi S, Sadighi S, Rouhi G. Comparison of three fixation methods for femoral neck fracture in young adults: experimental and numerical investigations. J Med Biol Eng. 2015;35:566–79.
13. Protzman RR, Burkhalter WE. Femoral-neck fractures in young adults. J Bone Joint Surg Am. 1976;58:689–95.
14. Collinge CA, Mir H, Reddix R. Fracture morphology of high shear angle "vertical" femoral neck fractures in young adult patients. J Orthop Trauma. 2014;28:270–5.
15. Liu J, Zhang B, Yin B, Chen H, Sun H, Zhang W. Biomechanical evaluation of the modified cannulated screws fixation of unstable femoral neck fracture with comminuted posteromedial cortex. Biomed Res Int. 2019;2019:2584151.
16. Huang TW, Hsu WH, Peng KT, Lee CY. Effect of integrity of the posterior cortex in displaced femoral neck fractures on outcome after surgical fixation in young adults. Injury. 2011;42:217–22.
17. Mittal R, Banerjee S. Proximal femoral fractures: principles of management and review of literature. J Clin Orthop Trauma. 2012;3:15–23.
18. Mir H, Collinge C. Application of a medial buttress plate may prevent many treatment failures seen after fixation of vertical femoral neck fractures in young adults. Med Hypotheses. 2015;84:429–33.
19. Ye Y, Chen K, Tian K, Li W, Mauffrey C, Hak DJ. Medial buttress plate augmentation of cannulated screw fixation in vertically unstable femoral neck fractures: surgical technique and preliminary results. Injury. 2017;48:2189–93.
20. Zhuang L, Wang L, Xu D, Wang Z. Anteromedial femoral neck plate with cannulated screws for the treatment of irreducible displaced femoral neck fracture in young patients: a preliminary study. Eur J Trauma Emerg Surg. 2019;45:995–1002.
21. Su Z, Liang L, Hao Y. Medial femoral plate with cannulated screw for Pauwels type III femoral neck fracture: a meta-analysis. J Back Musculoskelet Rehabil. 2021;34:169–77.
22. Zhenyu P, Aixi Y, Guo-Rong Y, Shaobo Z, Kai D. Treatment of serious femoral neck fractures with the transposition of vascularized greater trochanter bone flap in young adults. J Reconstr Microsurg. 2011;27:303–8.
23. Vallamshetla VR, Sayana MK, Vutukuru R. Management of ununited intracapsular femoral neck fractures by using quadratus femoris muscle pedicle bone grafting in young patients. Acta Orthop Traumatol Turc. 2010;44:257–61.
24. Xie X, Zhang C, Jin D, Chen S, Gao Y. Free vascularised fibular graft for neglected femoral neck fractures in young adults. Hip Int. 2012;22:319–23.
25. Yu X, Zhao D, Huang S, Wang B, Zhang X, Wang W, et al. Biodegradable magnesium screws and vascularized iliac grafting for displaced femoral neck fracture in young adults. BMC Musculoskelet Disord. 2015;16:329.
26. Li G, Jin D, Shao X, Liu Z, Duan J, Akilesh R, et al. Effect of cannulated screws with deep circumflex iliac artery-bone grafting in the treatment of femoral neck fracture in young adults. Injury. 2018;49:1587–93.
27. Baldwin P, Li DJ, Auston DA, Mir HS, Yoon RS, Koval KJ. Autograft, allograft, and bone graft substitutes: clinical evidence and indications for use in the setting of orthopaedic trauma surgery. J Orthop Trauma. 2019;33:203–13.
28. Zlowodzki M, Ayeni O, Petrisor BA, Bhandari M. Femoral neck shortening after fracture fixation with multiple cancellous screws: incidence and effect on function. J Trauma. 2008;64:163–9.
29. Chinese guideline for the diagnosis and treatment of osteonecrosis of the femoral head in adults. Orthop Surg. 2017;9:3–12.
30. Harris WH. Traumatic arthritis of the hip after dislocation and acetabular fractures: treatment by mold arthroplasty. An end-result study using a new method of result evaluation. J Bone Joint Surg Am. 1969;51:737–55.
31. Pei F, Zhao R, Li F, Chen X, Guo K, Zhu L. Osteonecrosis of femoral head in young patients with femoral neck fracture: a retrospective study of 250 patients followed for average of 7.5 years. J Orthop Surg Res. 2020;15:238.
32. Zhao G, Liu C, Chen K, Lyu J, Chen J, Shi J, et al. Nonanatomical reduction of femoral neck fractures in young patients (≤65 years old) with internal fixation using three parallel cannulated screws. Biomed Res Int. 2021;2021:3069129.
33. Dong Q, Han Z, Zhang YG, Sun X, Ma XL. Comparison of transverse cancellous lag screw and ordinary cannulated screw fixations in treatment of vertical femoral neck fractures. Orthop Surg. 2019;11:595–603.
34. Giordano V, Alves DD, Paes RP, Amaral AB, Giordano M, Belangero W, et al. The role of the medial plate for Pauwels type III femoral neck fracture: a comparative mechanical study using two fixations with cannulated screws. J Exp Orthop. 2019;6:18.
35. Li J, Yin P, Zhang L, Chen H, Tang P. Medial anatomical buttress plate in treating displaced femoral neck fracture a finite element analysis. Injury. 2019;50:1895–900.
36. Putnam SM, Collinge CA, Gardner MJ, Ricci WM, McAndrew CM. Vascular anatomy of the medial femoral neck and implications for surface plate fixation. J Orthop Trauma. 2019;33:111–5.