Arch Orthop Trauma Surg (2013) 133:125–133
DOI 10.1007/s00402-012-1623-3

HIP ARTHROPLASTY

# Core decompression and implantation of bone marrow mononuclear cells with porous hydroxylapatite composite filler for the treatment of osteonecrosis of the femoral head

**Yaosheng Liu · Shubin Liu · Xiuyun Su**

Received: 12 April 2012 / Published online: 16 October 2012


**Abstract**
*Background* Implanted bone marrow mononuclear cells (BMMCs) may promote both osteogenesis and angiogenesis in the femoral head. The aim of this study was to investigate the effectiveness of core decompression and implantation of BMMCs with porous hydroxyapatite bone filler for the treatment of osteonecrosis of the femoral head (ONFH).
*Methods* Patients with ONFH underwent core decompression and implantation of nano-hydroxyapatite/polyamide bone filler with or without BMMCs. Primary outcomes were changes in Harris hip and visual analogue scale (VAS) pain scores. Secondary outcomes included radiological and clinical success rates, adverse events, and complications.
*Results* Demographic/baseline characteristics were similar between groups (BMMC, $n = 17$ with 26 ONFH hips; control, $n = 17$ with 27 ONFH hips). Harris hip scores were significantly increased ($P < 0.05$) in both groups of patients after surgery (last follow-up). The magnitude of increase was significantly greater in the BMMC as compared with the control group (28.6 ± 0.5 vs. 18.4 ± 1.7 %, $P < 0.001$). VAS scores were significantly decreased ($P < 0.05$) in both groups after surgery (last follow-up). The magnitude of decrease was significantly greater in the BMMC as compared with the control group (−66.3 ± 1.4 vs. −51.7 ± 2.9 %, $P < 0.001$). Radiological and clinical success rates were significantly higher in the BMMC as compared with the control group (82.5 vs. 40.7 % and 75.4 vs. 37.0 %, respectively, $P < 0.001$). Postoperative collapse of the femoral head was less common in the BMMC as compared with the control group (17.5 vs. 59.3 %, $P < 0.01$).
*Conclusions* Both core decompression with or without implantation of BMMC are effective treatment for ONFH. However, core decompression with implantation of BMMCs and porous hydroxyapatite bone filler may be a more effective treatment for ONFH.

**Keywords** Osteonecrosis of the femoral head · Core decompression · Bone marrow mononuclear cell · Hydroxylapatite composite

## Introduction

Osteonecrosis of femoral head (ONFH) is a common cause of hip disability that, if left untreated, may cause collapse of femoral head and hip osteoarthritis in up to 80 % of patients within 4 years [1]. Although the etiology of ONFH is not completely understood, increased intramedullary pressure is believed to be a contributing factor. As such, core decompression, which is thought to reduce intramedullary pressure, improve/restore blood supply to the femoral head, and relieve pain, is a common early treatment for ONFH [2, 3]. Although core decompression is more effective than nonoperative treatment for the management ONFH [2], evidence from a systematic review revealed that the total clinical success rate of core decompression, with or without cancellous bone grafting, was only 63.5 %, and that subsequent joint replacement surgery or hip salvage surgery was necessary in 33 % of patients [1]. The variability in core decompression approaches used, in particular with regards to drilling and

Y. Liu · S. Liu (✉) · X. Su
Department of Orthopedic Surgery, The PLA 307th Hospital, No.8, Fengtaidongda Road, Beijing 100071, People's Republic of China
e-mail: lsb9126@126.com

filling of the core decompression tract, may explain much of the disparity between published findings [4]. Nevertheless, there is quite clearly room for further optimization of core decompression procedures in the treatment of ONFH.

A relatively recent, and promising, development in the treatment of ONFH is the implantation of autologous bone marrow mononuclear cells (BMMCs) in the core decompression tract. There is evidence to suggest that implanted BMMCs promote both osteogenesis and angiogenesis in the femoral head [5, 6]. These beneficial effects may be mediated, at least in part, by mesenchymal stem cells and endothelial precursor cells [7].

To date, the majority of reports concerning the implantation of BMMCs in the treatment of ONFH have involved implantation of concentrated BMMCs alone [5, 8–10]. To our knowledge, there has been only one preliminary study published describing outcomes associated with the implantation of BMMCs with porous material [7]. Implantation of BMMCs with a porous material may help promote bone formation [11]. The aim of our retrospective study was to examine the effectiveness of large diameter core decompression and implantation of BMMCs with porous hydroxyapatite composite bone filler for the treatment of ONFH.

## Patients and methods

### Patients

This study was a retrospective analysis of patients who received treatment for ONFH between June 2006 and January 2010 in the Orthopedic Department of the 307th Hospital of the People's Liberation Army. Osteonecrosis of the femoral head was diagnosed if magnetic resonance imaging (MRI; coronal and sagittal) revealed the following: belt-shaped or circular low intensity signals surrounded by high intensity signals in the outer area on short tau inversion; a high intensity area surrounded by belt-shaped or circular low intensity signals within the femoral head on T1-weighted images. Patients were eligible for inclusion in the study if they had Association Research Circulation Osseous (ARCO) stage I, II, or IIIA ONFH. Patients were excluded from the study if they had ARCO stage IIIB, IIIC, or IV ONFH. Patients with active infection, coagulation disorders, myelodysplastic syndrome, or anemia (hemoglobin <100 g/L, white blood cell count $<4 \times 10^9$ cells/L) were also excluded [12, 13]. There were two groups of patients in the study: a group who received core decompression and implantation of BMMCs (BMMC group) and a group who received core decompression without implantation of BMMCs (control group). Patients chose their preferred treatment approach after both options were clearly explained. There were only ARCO stage II ONFH patients in control group ($n = 17$). To match the study, we selected 17 age and gender matched ARCO stage II ONFH patients for BMMC group. The baseline demographic and clinical characteristics (including cause of ONFH, if known) of all patients were recorded.

### Surgical procedures

#### *Preparation of BMMCs*

Preoperative intravenous antibiotics were administered before surgery was performed under general anesthesia. Patients were placed in a prone position and a Gallini bone marrow aspiration needle was used to aspirate 150–200 mL bone marrow slowly and continuously from the posterior superior iliac spine of patients in the BMMC group. The direction of aspiration was changed after aspiration of each 5 mL of bone marrow, whereas the depth of aspiration was changed after each 20 mL (Fig. 1a). One mL of heparin saline (25,000 U heparin, 250 mL saline) was added to every 5 mL of bone marrow. Aspirated bone marrow was stored in a collection bag containing acid citrate dextrose.

After removing residual substances (i.e., fat tissue), bone marrow was gradient centrifuged using a blood cell separator (COBE Spectra; Gambro, Tokyo, Japan). BMMCs were isolated and purified using Cellgro medium (density 1.077 g/mL). A total of 5 mL of BMMCs were collected for treatment of unilateral ONFH and 10 mL were collected for bilateral ONFH. The mean concentration of BMMCs, as determined by cell counting, was $31.4 \pm 4.8 \times 10^6$ cells/mL. Cell viability was determined using the Trypan blue exclusion assay (satisfactory viability was indicated by $\geq$95 % viable cells). Blood agar plate culture and traditional microbial detection were performed to check for microbial contamination (these results were available after the completion of surgery). There was no evidence of contamination in any patient. The entire BMMC isolation and purification process took 90 min, during which time core decompression was performed.

### Core decompression and implantation of BMMCs

The operation was then conducted with the patient in a supine position with the affected hip prepared and freely draped. Under guidance of C-arm fluoroscopy, a 2.5 mm K-wire was inserted 3 cm inferior to the greater trochanter of the affected femur and inserted 5 mm inferior to the subchondral bone of the femoral head (the K-wire served as a guidewire). A 2 cm longitudinal skin incision was made and the subcutaneous fascia was dissected. A hollow drill with a 10 mm outer diameter was advanced along the guidewire 5 mm inferior to the subchondral bone of the

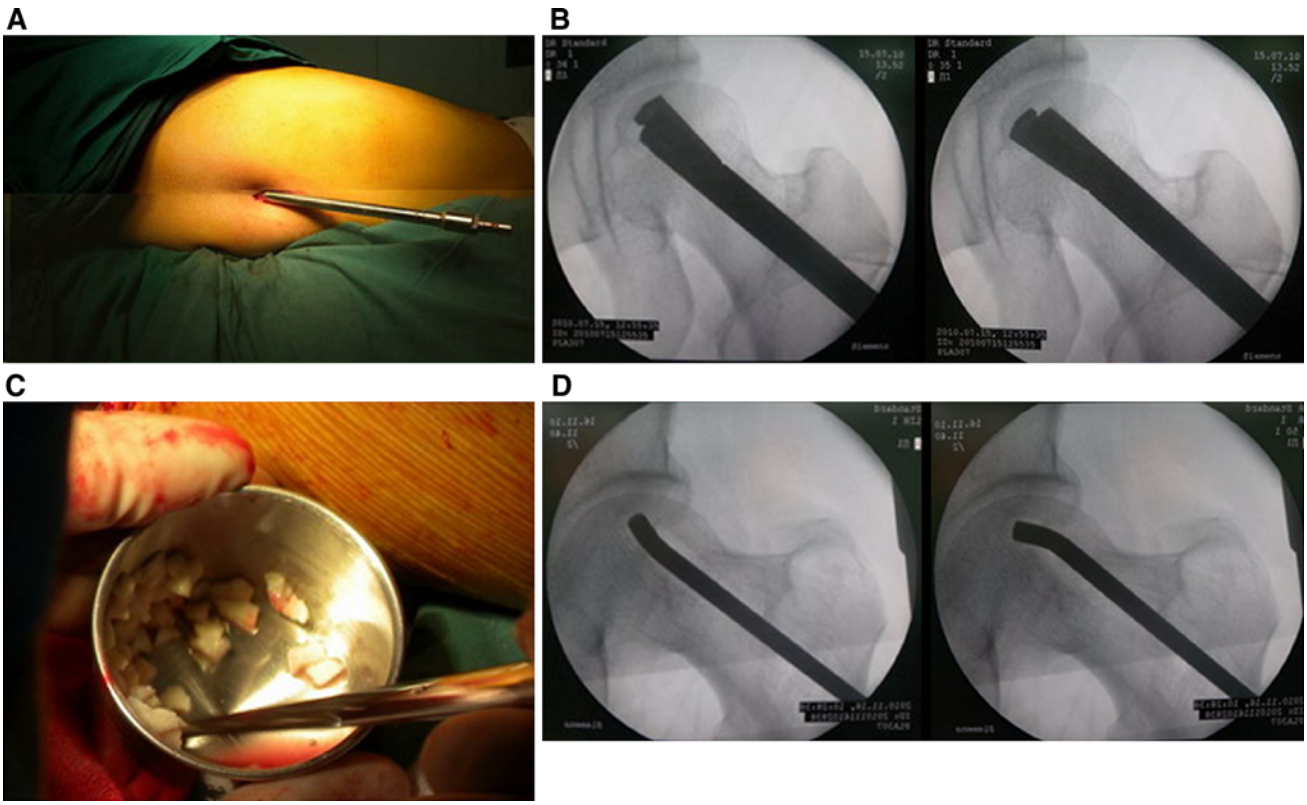


**Fig. 1** Surgical procedure. **a** After percutaneously inserting a 2.5 mm guidewire, a 10 mm drill bit was advanced along the guidewire 5 mm inferior to the subchondral bone. **b** Expanding reamers of various diameters were used to remove the sequestrum and sclerotic bone in the necrotic area of the femoral head. **c** Medical nano-hydroxyapatite/polyamide 66 composite bone filling material containing concentrated autologous bone marrow mononuclear cells (BMMCs). **d** The composite bone filling material containing concentrated BMMCs was compacted using a pushing bar. Reduction of the collapsed femoral head was performed for patients with stage IIIA osteonecrosis of the femoral head

femoral head (Fig. 1a). The hollow drill bit and guidewire were then removed, and expanding reamers of various diameters were used to progressively decompress the area of osteonecrosis (Fig. 1b). The sequestrum or bone marrow fat in the necrotic area was removed using a long-handled curette.

Granular porous medical nano-hydroxyapatite/polyamide 66 composite bone filling material (nano-apatite composite, Sichuan National Nano Technology Co., Ltd, Chengdu, China) was soaked in the concentrated BMMCs solution for 2 min (Fig. 1c). After the BMMC solution was completely absorbed, the bone filling particles/BMMCs were implanted in the bone tunnel. Repeated filling and compacting of the particles was performed using a pushing bar to ensure even filling (Fig. 1d). All patients with stage IIIA ONFH underwent reduction of the collapsed femoral head. After completion of core decompression and necrotic bone curettage under cartilage in femoral head weight-bearing area (i.e. femoral head anterior upper outside), artificial bone was gradually implanted into femoral head weight-bearing area through graft bone sleeve. Then, the collapsed femoral head area of IIIA ONFH reduction was completed through upward impact on artificial bone with different angle elbow and blunt head stick. Wound closure was performed after placing a suction drainage tube at the outer edge of the incision.

Control patients were treated as per the BMMC patients, except that the implanted bone filling particles did not contain BMMCs.

## Postoperative management and rehabilitation

The drainage tube was removed 24–48 h after surgery. Intravenous antibiotics were administered for the first 3 days after surgery to prevent wound infection. Sutures were removed 2 weeks after surgery. Weight-bearing was not allowed within the first 3 months after surgery. Partial weight-bearing crutch walking was allowed thereafter and full weight-bearing was allowed 6 months after surgery. Patients were allowed to engage in physical activities and sports 12 months after surgery.

### Follow-up and outcome measures

Clinical function and imaging evaluations were performed every 6 months after surgery and at the last follow-up visit.

The primary outcome measures were the changes from before surgery to after surgery (last follow-up) in the Harris hip score and visual analogue scale (VAS) pain score. The maximum Harris hip score is 100 points, indicating no disability. "Excellent" scores are 90–100; "good" scores are 80–89; "fair" scores are 70–79; and "poor" scores are 60–69. For VAS scores, 0 was defined as no pain, 0–3 mild pain, 4–6 endurable pain affecting sleep, and 7–10 unendurable severe pain.

Secondary outcome measures included radiological and clinical success rates, adverse events, and complications. Radiological success was indicated by a lack of femoral head collapse and/or development of osteoarthritis in the hip joint. The clinical success rate was defined as the proportion of patients with postoperative Harris hip scores ≥80 [14]. Anteroposterior and frog leg lateral hip radiographs were obtained to assess healing of the femoral head.

### Statistical analysis

Continuous and categorical demographic and baseline measurements were compared between groups by independent two-sample *t* test and Chi-square/Fisher's exact test, respectively. Continuous variables are presented as mean ± standard deviation, whereas categorical variables are presented as number and percentage. Linear mixed models were used to compare changes in Harris hip and VAS scores between the two groups because of dependent samples (some patients underwent bilateral procedures). Linear mixed models were also used to compare Harris hip and VAS scores before and after surgery in both groups. Continuous clinical variables are presented as mean ± standard error. All statistical assessments were two-sided and evaluated at the 0.05 level of statistical significance. Statistical analyses were performed using SPSS 15.0 statistical software (SPSS Inc, Chicago, IL).

## Results

### Demographics and baseline characteristics

There were 17 patients in each group (eight single and nine bilateral hips for BMMC group; seven single and ten bilateral hips for control group), which had matched age, gender and ARCO stage disease (IIB and IIC only). The demographics and baseline characteristics were similar between the two groups (Table 1). Patients were aged between 26 and 51 years and the majority (≥76.5 %) in both groups were male. The duration of follow-up ranged from 12 to 40 months in the BMMC group, and 18 to 32 months in the control group. Most (≥58.8 %) patients had bilateral ONFH caused by alcohol abuse (≥51.9 %). Mean preoperative Harris hip scores were poor in both groups, while mean preoperative VAS scores indicated that patients in both groups were experiencing endurable pain affecting sleep.

**Table 1** Demographic and baseline characteristics of patients with osteonecrosis of the femoral head

| Characteristic | BMMC ($n = 17$) | Control ($n = 17$) | $P$ value |
|---|---|---|---|
| Age (years)[a] | 38.0 ± 4.9 | 38.1 ± 6.1 | 0.514 |
| Gender, *n* (%)[b] | | | 1.000 |
| Male | 13 (76.5) | 14 (82.4) | |
| Female | 4 (23.5) | 3 (17.6) | |
| Hips, *n* (%)[c] | | | 0.730 |
| Single | 8 (47.1) | 7 (41.2) | |
| Bilateral | 9 (52.9) | 10 (58.8) | |
| Follow-up (months)[a] | 26.7 ± 8.0 | 24.9 ± 4.5 | 0.432 |
| Number of hips | 28 | 27 | |
| Etiology, *n* (%)[b] | | | 1.000 |
| Corticosteroid-induced | 10 (35.7) | 9 (33.3) | |
| Alcohol abuse | 15 (53.6) | 14 (51.9) | |
| Idiopathic | 3 (10.7) | 4 (14.8) | |
| ARCO Stage, *n* (%)[c] | | | 0.883 |
| IIB | 13 (46.4) | 12 (44.4) | |
| IIC | 15 (53.6) | 15 (55.6) | |
| Harris hip score[d] | 63.6 ± 2.6 | 64.6 ± 2.9 | 0.196 |
| VAS[d] | 6.36 ± 0.95 | 6.26 ± 0.66 | 0.661 |

Data are presented as mean ± standard deviation or number (percentage) and were compared between groups by [a]independent two-sample *t* test, [b]Fisher's exact test, [c]Chi-square test, or [d]linear mixed model

*ARCO* Association Research Circulation Osseous, *VAS* visual analogue scale

### Changes in Harris hip and VAS scores after treatment

At last follow-up, Harris hip scores were significantly increased ($P < 0.05$) when compared before surgery in both patient groups (Fig. 2a). The magnitude of increase in the BMMC group was significantly greater than that in the control group (28.6 ± 0.5 vs. 18.4 ± 1.7 %, $P < 0.001$).

At last follow-up, VAS scores were significantly decreased ($P < 0.05$) when compared before surgery in both patient groups (Fig. 2b). The magnitude of decrease was significantly greater ($P < 0.001$) in the BMMC group (−66.3 ± 1.4 %) as compared with the control group (−51.7 ± 2.9 %).

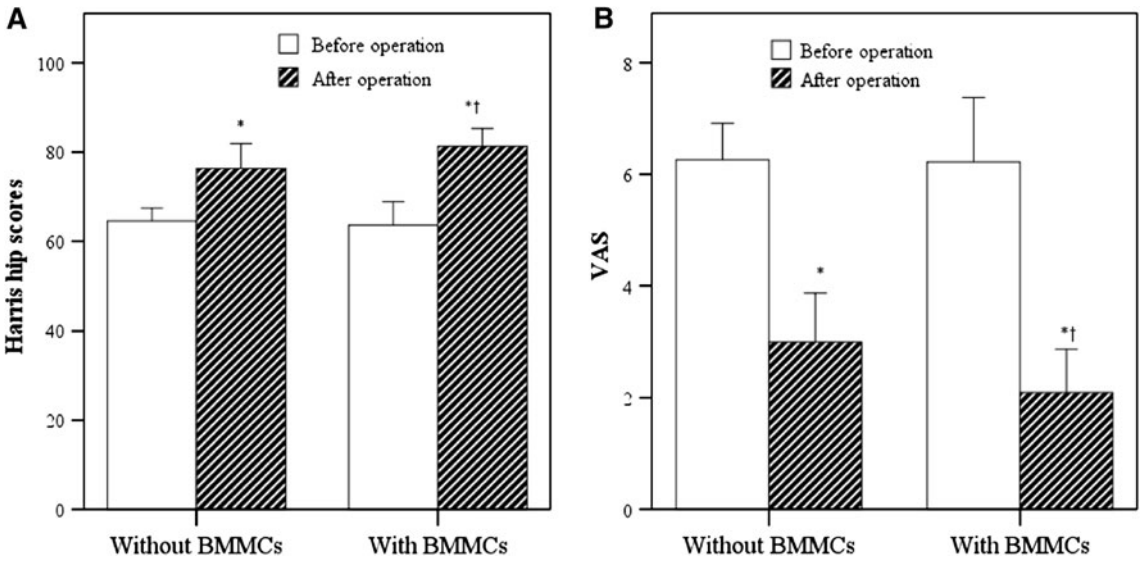


**Fig. 2** **a** Harris hip and **b** visual analogue scale (VAS) scores before and after (last follow-up) patients with osteonecrosis of the femoral head underwent core decompression and implantation of porous hydroxyapatite composite bone filler with or without bone marrow mononuclear cells (BMMC ($n = 28$ hips) and control ($n = 27$ hips) groups, respectively). Data are presented as mean ± standard error and were compared using a linear mixed model. *indicates a statistically significant difference ($P < 0.05$, before vs. after surgery). †indicates a statistically significant difference between the BMMC and the control groups, $P < 0.05$

There was no significant difference in the magnitude of improvement between patients in the control and BMMC group with ARCO stage IIB and IIC (Fig. 3a). The magnitude of improvement in the Harris hip score for patients with ARCO stage IIB or IIC was significantly greater in the BMMC group as compared with the control group ($P < 0.05$).

There was significant difference in the magnitude of improvement in the VAS score between BMMC patients with ARCO stage IIB and IIC (Fig. 3b). However, there was no significant difference in the magnitude of improvement between patients in the control group with ARCO stage IIB and IIC. The magnitude of improvement in the VAS score for patients with ARCO stage IIB or IIC was significantly greater in the BMMC group as compared with the control group ($P < 0.05$).

## Radiological and clinical success rates, adverse events, and complications

The radiological success rate was significantly higher ($P = 0.004$) in the BMMC group (78.6 %) as compared

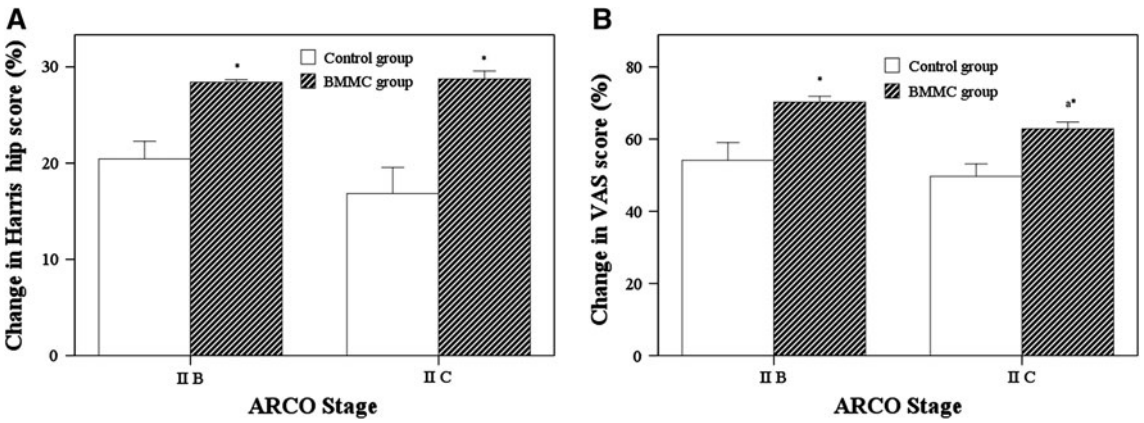


**Fig. 3** Percentage changes in **a** Harris hip and **b** visual analogue scale (VAS) scores by Association Research Circulation Osseous (ARCO) stage in patients with osteonecrosis of the femoral head after core decompression and implantation of porous hydroxyapatite composite bone filler with or without bone marrow mononuclear cells (BMMC ($n = 28$ hips) and control ($n = 27$ hips) groups, respectively). Postoperative assessments were made at last follow-up. Data are presented as mean ± standard error and were compared using a linear mixed model. [a]Indicates a statistically significant difference between Stage IIB and IIC ($P < 0.05$). *indicates a statistically significant difference between the BMMC and the control groups, $P < 0.05$

with the control group (40.7 %). The clinical success rate was higher (75.4 %) in the BMMC group as compared with the control group (37.0 %).

There were no between-group differences in the rates of guidewire breakage ($n = 2/28$, 7.1 % in the BMMC group and 2/27, 7.4 % in the control group) or perforation of the subchondral bone ($n = 1/28$, 3.6 % in the BMMC group and 3/27, 11.1 % in the control group). The guidewire was bent in case of insertion into very hard areas of necrosis. The bent guidewire would be broken when the hollow drill went through it. Broken guidewires were removed under intraoperative fluoroscopic guidance. Perforation of the subchondral bone resulted in temporary mild pain in the inguinal area. In each instance, this pain gradually decreased and had disappeared 3 months after surgery with subchondral bone healing.

In the BMMC group, 21.4 % (6/28) of hips exhibited collapse or aggravated collapse of the femoral head in the weight-bearing area. Newly developed osteoarthritis of the hip joint was detected in four of these hips, and artificial hip joint replacement was needed. Postoperative X-ray 12 months after surgery revealed a relatively significant sclerotic zone around the margin of the original necrotic area in one patient in the BMMC group. Follow-up X-ray 6 months later revealed that there was no change in the margin of the necrotic area and secondary percutaneous multi-channel (3 mm diameter) core decompression was performed. Follow-up X-ray 5 months after the second surgery revealed that the extent of necrosis had decreased significantly and that there was no further collapse of the femoral head.

In the control group, 59.3 % (16/27) of hips exhibited collapse or aggravated collapse of the femoral head in the weight-bearing area. Newly developed osteoarthritis of the hip joint was detected in five hips, and artificial hip joint replacement was needed.

There were no instances of hematoma at the posterior superior iliac spina, postoperative hip joint infection or neurovascular injury in either group. We did not observe any clinical deterioration in either group during the follow-up period.

Radiographic images from a representative successful case of a patient with stage IIB osteonecrosis of the femoral head successfully treated at 18 months after the surgery in BMMC group (Fig. 4) and a representative unsuccessful case of a patient with stage IIIA osteonecrosis of the femoral head unsuccessfully treated with femoral head collapse at 12 months after the surgery in BMMC group (Fig. 5).

## Discussion

In this study, we examined the effectiveness of large diameter core decompression and implantation of BMMCs with porous hydroxyapatite composite bone filler for the treatment of ONFH. When compared to patients who were treated with core decompression and implantation of the

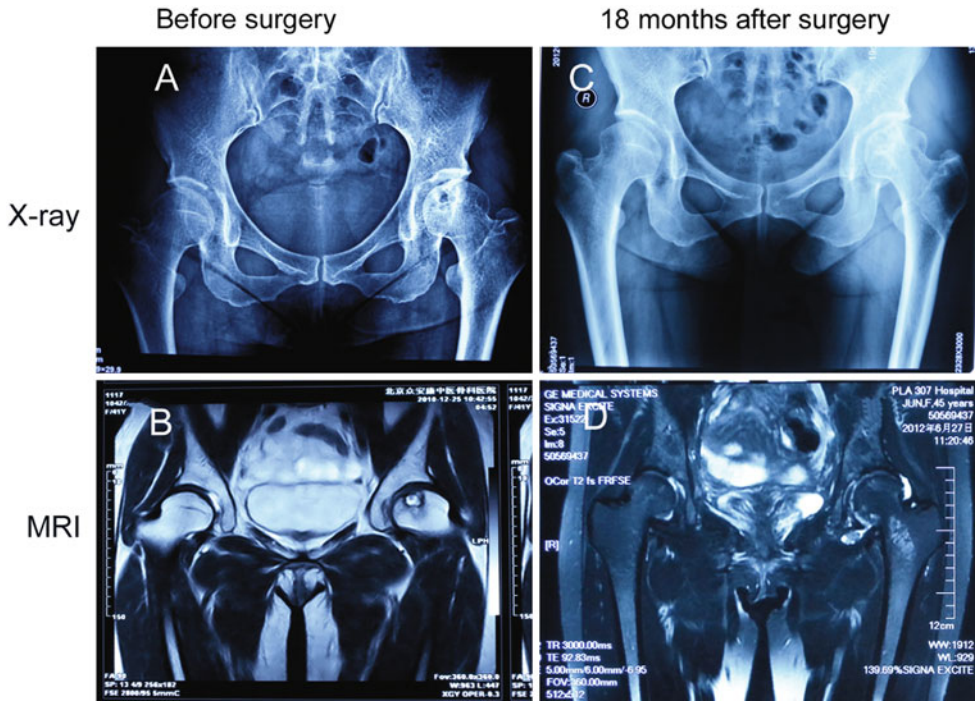


**Fig. 4** Radiographs from a representative case in which a patient with stage IIB osteonecrosis of the femoral head was successfully treated with core decompression and implantation of bone marrow mononuclear cells with porous hydroxyapatite bone filler. X-ray and magnetic resonance images are shown as taken before surgery (**a**, **b**) and 18 months after surgery (**c**, **d**)

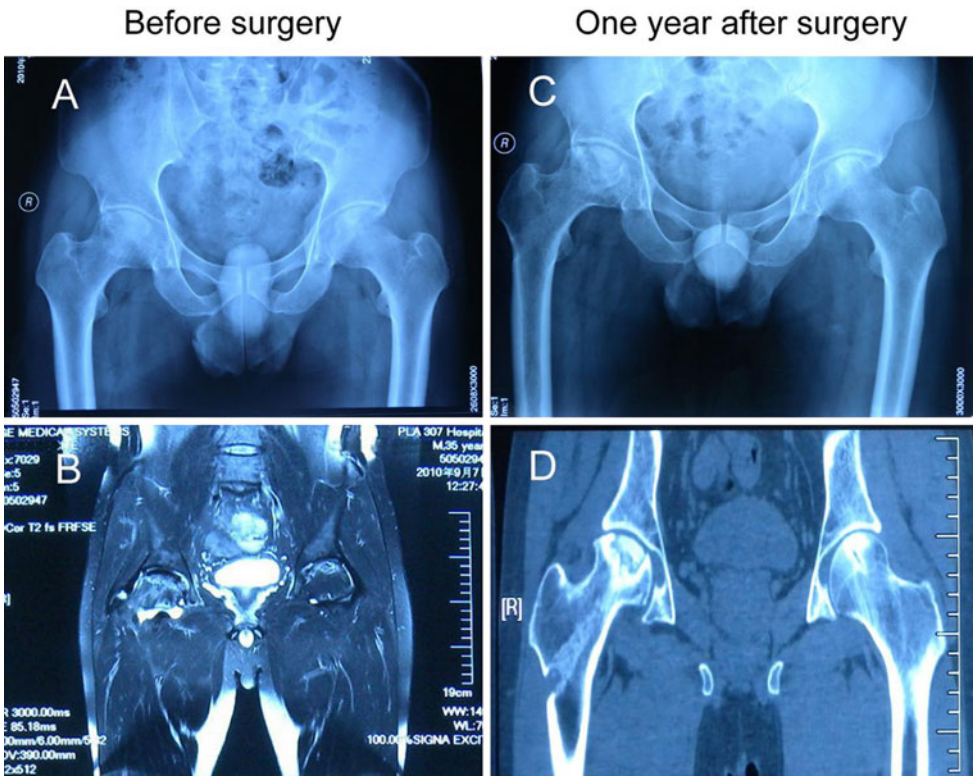


**Fig. 5** Radiographs from a representative case in which a patient with stage IIIA osteonecrosis of the femoral head was unsuccessfully treated with core decompression and implantation of bone marrow mononuclear cells with porous hydroxyapatite bone filler. Femoral head collapse was evident 12 months after surgery. X-ray (**a**, **c**), magnetic resonance image (**b**) and CT (**d**) are shown as taken before surgery (**a**, **b**) and 12 months after surgery (**c**, **d**). No MRI image was taken for this patient in the follow-up

composite bone filler alone, we found that patients who were treated with core decompression and implantation of composite bone filler with BMMCs had better outcomes as indicated by significantly greater improvements in Harris hip and VAS scores. Radiological healing success rates were also significantly higher for patients in the BMMC group as compared with the control group. Importantly, a far lower proportion of hips exhibited postoperative collapse or aggravated collapse of the femoral head in the BMMC group as compared with the control group. These findings suggest that core decompression and implantation of BMMCs with porous hydroxyapatite composite bone filler may be an effective treatment for early ONFH.

To our knowledge, this is the first study to quantitatively assess outcomes following core decompression and the implantation of BMMCs with porous material for the treatment of ONFH. We found that both hip function and pain, assessed using the Harris hip score and a VAS, were significantly improved after surgery in both groups, but significantly more so in the group of patients who were treated with BMMCs. The radiological and clinical success rates were also markedly higher in the BMMC group as compared with the control group. Our findings are consistent with those reported by Yamasaki et al. [7] who found greater clinical improvement (evaluated using the rating system of Merle d'Aubigné and Postel) in patients treated with core decompression and implantation of a porous hydroxyapatite scaffold with BMMCs versus patients treated with core decompression and implantation scaffold alone. Also consistent with our findings, Gangji and colleagues [8, 10] have reported decreased pain (VAS) and joint symptoms (evaluated using the Lequesne and WOMAC indices) in patients treated with core decompression and implantation of BMMCs (without porous bone filler) versus patients treated with core decompression alone. Other studies that did not include control groups have found that core decompression (of various diameters) and implantation of concentrated BMMCs (without porous bone filler) facilitated improved hip function and relatively high rates of radiological success in patients with ONFH [5, 9, 15].

Large diameter core decompression was used for all patients in our study. We believe that small diameter multichannel core decompression is suitable for precollapsed lesions with a small range of necrosis, as previously suggested [16], such as ARCO stage IA ONFH. However, we suggest that most patients with early and middle stage (>IA) ONFH should be treated with conventional large diameter core decompression. Large diameter core decompression offers several advantages. One advantage is that high pressure within the necrotic femoral head could achieve sufficient decompression. A second advantage is that progressively expanding reamers can be used to completely remove the sequestrum and fatty marrow within the necrotic area. Other potential advantages, more specific to implantation of porous bone filler with BMMCs

after core decompression, may include; enhanced differentiation and proliferation of BMMCs; improved colony-forming ability of bone marrow stem cells; decreased risk of postnecrotic collapse in the weight-bearing area of the femoral head because of impaction bone grafting after core decompression of the anterolateral necrotic area; and the availability of sufficient support to facilitate reduction of the collapsed femoral head in patients with stage IIIA ONFH.

In this study, postoperative anterolateral collapse or aggravated collapse of the femoral head occurred in slightly less than 20 % of hips of patients in the BMMC group, a far lower proportion than in the control group. These complications may have been a consequence of subchondral bone perforation due to large diameter core decompression, inaccurate or incomplete bone graft compaction, and/or early postoperative weight-bearing. Subchondral bone perforation of the sclerotic zone of the femoral head is a potential complication of large diameter core decompression involving use of a hollow drill. Thus, radiological monitoring during core decompression is important. After core decompression is complete, a pushing bar should be carefully employed to optimize bone graft compaction. In cases where intraoperative subchondral bone perforation has occurred, we suggest that postoperative complete weight-bearing on the affected hip should be delayed. Follow-up frog leg and anteroposterior radiographs should be performed every 3 months after surgery to assess healing. Weight-bearing should only be allowed once the implanted artificial bone forms autogenous bone, typically around 6 months after surgery.

Our study has several limitations that must be acknowledged. Of note, the number of patients included in our study does not allow us to make any definitive conclusions with reference to the study findings. The retrospective nature of our study is another obvious limitation. Quite clearly, prospective studies involving a larger number of patients are needed, as are studies comparing core decompression and implantation of BMMCs with porous hydroxyapatite composite bone filler with other treatment approaches for ONFH, in particular core decompression alone. Further studies are also needed to more comprehensively determine the longer term efficacy of the treatment approach described in this study and to determine which patients might be more likely to benefit from this treatment approach. Another limitation is that, because few patients underwent MRI during follow-up, we were unable to monitor bone formation in the necrotic area or examine how this may have affected outcomes. Future studies should incorporate such monitoring. A final limitation is that we cannot be certain that implanted BMMCs remained at the site of implantation. The BMMC solution was, however, completely absorbed by the bone filling material before implantation; hence, we are confident that any loss would be minimal. Nevertheless, confirmatory in vivo studies are needed.

In conclusion, we have found that large diameter core decompression and implantation of concentrated autologous BMMCs with porous hydroxylapatite composite bone filler can significantly decrease hip pain, improve hip function, and prevent collapse of the femoral head in patients with ONFH. The effectiveness of this approach may vary with ARCO stage. We suggest that this treatment approach may be suitable for patients with early to middle stage ONFH.

**Acknowledgments** The experiments described in this manuscript comply with the current laws of the People's Republic of China.

**Conflict of interest** The authors declare that they have no conflict of interest.

## References

1. Mont MA, Carbone JJ, Fairbank AC (1996) Core decompression versus nonoperative management for osteonecrosis of the hip. Clin Orthop Relat Res 324:169–178
2. Lieberman JR (2004) Core decompression for osteonecrosis of the hip. Clin Orthop Relat Res 418:29–33
3. Song WS, Yoo JJ, Kim YM, Kim HJ (2007) Results of multiple drilling compared with those of conventional methods of core decompression. Clin Orthop Relat Res 454:139–146
4. Marker DR, Seyler TM, Ulrich SD, Srivastava S, Mont MA (2008) Do modern techniques improve core decompression outcomes for hip osteonecrosis? Clin Orthop Relat Res 466:1093–1103
5. Hernigou P, Beaujean F (2002) Treatment of osteonecrosis with autologous bone marrow grafting. Clin Orthop Relat Res 405:14–23
6. Sun Y, Feng Y, Zhang C (2009) The effect of bone marrow mononuclear cells on vascularization and bone regeneration in steroid-induced osteonecrosis of the femoral head. Jt Bone Spine 76:685–690
7. Yamasaki T, Yasunaga Y, Ishikawa M, Hamaki T, Ochi M (2010) Bone-marrow-derived mononuclear cells with a porous hydroxyapatite scaffold for the treatment of osteonecrosis of the femoral head: a preliminary study. J Bone Jt Surg Br 92:337–341
8. Gangji V, Hauzeur JP, Matos C, De Maertelaer V, Toungouz M, Lambermont M (2004) Treatment of osteonecrosis of the femoral head with implantation of autologous bone-marrow cells. A pilot study. J Bone Jt Surg Am 86-A:1153–1160
9. Wang BL, Sun W, Shi ZC et al (2010) Treatment of nontraumatic osteonecrosis of the femoral head with the implantation of core decompression and concentrated autologous bone marrow containing mononuclear cells. Arch Orthop Trauma Surg 130:859–865
10. Gangji V, De Maertelaer V, Hauzeur JP (2011) Autologous bone marrow cell implantation in the treatment of non-traumatic osteonecrosis of the femoral head: five year follow-up of a prospective controlled study. Bone 49:1005–1009
11. Ito Y, Tanaka N, Fujimoto Y et al (2004) Bone formation using novel interconnected porous calcium hydroxyapatite ceramic hybridized with cultured marrow stromal stem cells derived from Green rat. J Biomed Mater Res A 69:454–461

12. Wang CJ, Wang FS, Huang CC, Yang KD, Weng LH, Huang HY (2005) Treatment for osteonecrosis of the femoral head: comparison of extracorporeal shock waves with core decompression and bone-grafting. J Bone Jt Surg Am 87:2380–2387
13. Wang CJ, Wang FS, Yang KD et al (2008) Treatment of osteonecrosis of the hip: comparison of extracorporeal shockwave with shockwave and alendronate. Arch Orthop Trauma Surg 128:901–908
14. Wang BL, Sun W, Shi ZC et al (2010) Treatment of nontraumatic osteonecrosis of the femoral head using bone impaction grafting through a femoral neck window. Int Orthop 34:635–639
15. Daltro GC, Fortuna VA, Salvino de Araújo SA, FerrazLessa PI, Sobrinho UA, Borojevic R (2008) Femoral head necrosis treatment with autologous stem cells in sickle cell disease. Acta Orthop Bras 16:44–48
16. Kim SY, Kim DH, Park IH, Park BC, Kim PT (2003) Ihn JC Multiple drilling compared with core decompression for the treatment of osteonecrosis of the femoral head. Read at the Annual Meeting of the Association Research Circulation Osseous; Oct 9–11; Jeju Island, South Korea