Risk Stratification for Avascular Necrosis of the Femoral Head After Internal Fixation of Femoral Neck Fractures by Post-Operative Bone SPECT/CT

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Abstract

Purpose Avascular necrosis (AVN) of the femoral head is a major complication after internal fixation of a femoral neck fracture and determines the functional prognosis. We investigated postoperative bone single-photon emission computed tomography/computed tomography (SPECT/CT) for assessing the risk of femoral head AVN.

Methods We retrospectively reviewed 53 consecutive patients who underwent bone SPECT/CT within 2 weeks of internal fixation of a femoral neck fracture and follow-up serial hip radiographs over at least 12 months.

Results Nine patients developed femoral head AVN. In 15 patients who showed normal uptake on immediate postoperative SPECT/CT, no AVN occurred, whereas 9 of 38 patients who showed cold defects of the femoral head later developed AVN. The negative predictive value of immediate postoperative SPECT/CT for AVN was 100 %, whereas the positive predictive value was 24 %. Among 38 patients with cold defects, 1 developed AVN 3 months postoperatively. A follow-up bone SPECT/CT was performed in the other 37 patients at 2–10 months postoperatively. The follow-up bone SPECT/CT revealed completely normalized femoral head uptake in 27,

partially normalized uptake in 8, and persistent cold defects in 2 patients. AVN developed in 3.7 % (1/27), 62.5 % (5/8), and 100 % (2/2) of each group, respectively.

Conclusions According to the time point of imaging, radio-tracer uptake patterns of the femoral head on postoperative bone SPECT/CT indicate the risk of AVN after internal fixation of femoral neck fractures differently. Postoperative bone SPECT/CT may help orthopedic surgeons determine the appropriate follow-up of these patients.

Keywords Bone SPECT/CT · Avascular necrosis · Femoral neck fracture · Internal fixation

Introduction

Femoral neck fractures are not only a life-threatening lesion in the elderly, with a mortality rate of 20–30 % [1], but also cause serious disability in the young. The increasing proportion of the older population has been accompanied by an increase in the incidence of femoral neck fractures [2]. These fractures can be managed by internal fixation or primary arthroplasty. Physiologic age and the degree of displacement of the fracture are the main factors for determining the method of operation [3, 4]. Although the optimal choice for management remains controversial, internal fixation is generally preferred in young patients with undisplaced fractures in whom the therapeutic goal is to save the natural femoral head. However, in older patients with displaced fractures, primary arthroplasty is commonly performed to restore mobility.

One of the main complications after internal fixation of a femoral neck fracture is avascular necrosis (AVN) of the femoral head [5]. The overall incidence of AVN of the femoral head after internal fixation of a femoral neck fracture is 15–

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25 % [6–9]. A significant proportion of those who develop AVN complain of disabling pain and require secondary arthroplasty because of secondary osteoarthritis [6, 10]. Femoral head collapse is considered the most important functional prognostic factor in progression to secondary osteoarthritis [11]. Joint-preserving procedures, such as core decompression or vascularized fibular grafts, can be performed more successfully at an earlier stage of AVN to prevent progression in severity and joint destruction [11–13]. Hence, early prediction of developing AVN is critical for assessing the functional prognosis and planning further therapeutic approaches.

Disruption of the blood supply to the femoral head at the time of injury is considered to underlying AVN of the femoral head following femoral neck fracture [14]. Vascular damage induces bone cell ischemia and subsequent cell death, followed by structural changes [15]. As absent radiotracer uptake on bone scintigraphy reflects disrupted blood supply to bone tissue, a cold defect in the femoral head is considered an early scintigraphic sign of osteonecrosis of the femoral head. There are several studies on the usefulness of planar bone scintigraphy for predicting AVN of the femoral head after internal fixation of femoral neck fractures [16–22]. However, the time when bone scintigraphy was performed varies, and the predictive values were different for each study. Therefore, it remains unclear whether these inconsistent reports result from limited performance of bone scintigraphy for assessing the blood supply to the femoral head or the different time points of imaging. Bone single-photon emission computed tomography (SPECT) has a better diagnostic ability for detecting cold defects of the femoral head than planar bone scintigraphy on which the cold femoral head may be obscured by other surrounding activities [23, 24]. In addition to SPECT imaging, hybrid imaging of SPECT and computed tomography (CT) provides complex anatomical information on the hip and attenuation correction of SPECT images. Despite the improved diagnostic performance of SPECT/CT over planar scintigraphy, no studies have investigated the usefulness of bone SPECT/CT for AVN of the femoral head after femoral neck fracture.

We hypothesized that postoperative bone SPECT/CT might stratify the risk of AVN of the femoral head after internal fixation of femoral neck fractures and the time point of the scan might affect its risk assessment ability. Therefore, this study was performed to investigate the relationship between radiotracer uptake patterns of the femoral head on postoperative bone SPECT/CT and subsequent occurrence of AVN of the femoral head and whether it is different according to the time point of imaging in patients who underwent internal fixation of a femoral neck fracture.

Materials and Methods

Subjects

We retrospectively reviewed consecutive patients who underwent internal fixation for a femoral neck fracture between November 2007 and October 2014 in our institution. Among a total of 112 patients, 91 underwent immediate post-operative bone SPECT/CT for assessment of the blood supply to the femoral head within 2 weeks of surgery. Twenty-nine patients with less than 1 year of follow-up after surgery were excluded from the analysis. Patients with previous osteonecrosis of the femoral head ($n = 1$), contralateral femoral neck fracture ($n = 1$), pathologic fracture ($n = 2$), previous organ transplantation ($n = 4$), and a history of oral steroid medication ($n = 1$) were also excluded. Finally, we analyzed 53 patients. Their mean age was 59.1 years (range, 31–82 years). Fourteen were male and 39 were female. No patient enrolled in this study had a history of trauma during follow-up period.

This study was approved by our Institutional Review Board (IRB no. 2016–0231). The Institutional Review Board waived the need to obtain informed consent.

Surgical Treatment and Follow-Up

Femoral neck fractures were classified by Garden's classification [25]. Garden stage I is an incomplete fracture including a valgus impacted fracture, stage II is a complete fracture without displacement, stage III is a complete fracture with partial displacement, and stage IV is a complete fracture with full displacement. Stages I and II were classified as undisplaced fractures, and stages III and IV were classified as displaced fractures.

We generally performed internal fixation in patients younger than 65 years with undisplaced femoral neck fractures and primary arthroplasty in patients older than 65 years with displaced fractures. In young patients with displaced femoral neck fractures, internal fixation is considered to be the primary treatment because of their functional demands and the longevity of the prosthetic joint. Internal fixation is also preferred because of the reduced bleeding and shorter operation times in patients older than 65 years with concurrent medical problems. Surgical fixation was performed as soon as possible after admission. Closed reduction was performed under C-arm guidance by internal rotation while applying longitudinal traction to the lower limb. Internal fixation of the femoral neck fracture was performed with three cannulated screws in an inverted triangle shape after the reduction had been confirmed. Capsulotomy or aspiration of the hematoma was not performed. Patients received continuous passive motion on the first day after surgery and were instructed to use a walker or crutches for partial weight bearing for 12 weeks. A full weight

load without any devices was permitted 12 weeks after surgery.

Plain radiography was performed to assess fracture healing and identify AVN of the femoral head at 6 weeks, 3 months, 6 months, and 12 months after surgical fixation. AVN of the femoral head was diagnosed when patch sclerosis and cystic changes, subchondral collapse, or flattening of the femoral head were detected on plain radiographs. The severity of AVN was retrospectively classified by one experienced orthopedic surgeon (J.K.) using the Ficat classification [26].

Bone SPECT/CT Acquisition and Image Analysis

The immediate postoperative bone SPECT/CT was performed within 2 weeks after surgery. In patients who showed a cold defect of the ipsilateral femoral head, the follow-up bone SPECT/CT was performed 2–10 months later.

Bone SPECT/CT, including both hips, was performed approximately 4 h after intravenous injection of 1,110 MBq of ^{99m}Tc -diphosphono-1,2-propanodicarboxylic acid (^{99m}Tc -DPD) using a hybrid dual-head gamma camera and 16-slice CT system (Precedence 16; Philips Healthcare, Best, The Netherlands) equipped with a low-energy high-resolution parallel-hole collimator. Patients were asked to void before the start of SPECT/CT acquisition. SPECT images were acquired in step-and-shoot mode with non-circular rotation, 20 s per projection, 64 projections over 360 degrees, and a 128×128 matrix after hip CT for attenuation correction and image fusion. Hip CT scanning was performed in helical mode at 120 kVP and 50 mAs with a slice thickness of 3.3 mm. The SPECT images were reconstructed with iterative reconstruction in AutoSPECT+ software and Astonish (Philips Healthcare, Best, The Netherlands) with 4 iterations and 16 subsets and a Hanning filter with a cutoff frequency of 1.0.

The bone SPECT/CT images were retrospectively reviewed by two experienced nuclear medicine physicians (M.O. and S.Y.) who were unaware of patient identification and clinical information, independently. Discordant findings were resolved by consensus. On the immediate postoperative bone SPECT/CT, tracer uptake of the ipsilateral femoral head to the fracture was visually classified as “normal uptake,” “complete cold defect” (absent radiotracer uptake of total femoral head), or “partial cold defect (absent radiotracer uptake of some portion of femoral head) compared with that of the contralateral side. Both “complete cold defect” and “partial cold defect” are considered as a cold defect of the femoral head. On the follow-up postoperative bone SPECT/CT, femoral head uptake was compared with that of the immediate postoperative bone SPECT/CT and then classified as “completely normalized uptake,” “partially normalized uptake,” or “persistent cold defect.” In the “partially normalized uptake” group, the extent of the remaining cold defect was visually estimated as the percentage of the femoral head

compared with the area of the whole femoral head as $\leq 30\%$ and $>30\%$ [11].

Statistical Analysis

SPSS for Windows (version 21.0; SPSS Inc., Chicago, IL, USA) was used for statistical analyses. The Kolmogorov-Smirnov test was used to confirm whether continuous data fit the normal distribution. An independent t-test was performed to compare continuous variables between the AVN and no-AVN groups. Fisher’s exact test was used to compare categorical variables between the two groups. A *P* value of less than 0.05 was regarded as statistically significant. The positive and negative predictive values (PPV and NPV) of postoperative bone SPECT/CT were calculated.

Results

Patient Characteristics

According to Garden’s classification, 30 patients were stage I, 9 patients were stage II, 8 patients were stage III, and 6 patients were stage IV. The mean follow-up period was 29.5 months. The median time interval from injury to internal fixation was 31 h. Twenty-three of 53 patients underwent surgery within 24 h. In the other 30 patients, surgery was delayed because of transfer from the local clinic to our center ($n = 21$), neglected fracture ($n = 5$), multiple trauma ($n = 2$), or other medical problems ($n = 2$).

AVN of the femoral head occurred in 9 (17.0 %) of 53 patients on follow-up radiographs after internal fixation of the femoral neck fracture (3 patients with Ficat stage II, 5 with Ficat stage III, and 1 with Ficat stage IV). AVN of the femoral head was detected on radiograph at a mean 19.3 months (range, 3–37 months) after surgery. In patients with undisplaced fractures, AVN did not occur. All AVNs developed in patients with displaced fractures (three of eight patients with Garden stage III and six of six patients with stage IV). The association between the Garden stage of the fracture and the outcome was statistically significant ($P < 0.001$). No statistically significant relationship was found between the time interval to surgery and later AVN occurrence ($P = 0.715$). The baseline characteristics of patients according to later AVN occurrence are summarized in Table 1.

Incidence of AVN According to Postoperative Bone SPECT/CT Findings

Figure 1 shows the incidence of AVN of the femoral head according to postoperative bone SPECT findings. On the immediate postoperative bone SPECT/CT within 2 weeks after surgery (range 1–14 days, mean 4.1 days), 15 patients showed

Table 1 Baseline patient characteristics according to the occurrence of later avascular necrosis

Characteristics	Total (n = 53)	AVN (n = 9)	No AVN (n = 44)	P value
Age				0.463
<65 years	34 (64.2 %)	7 (77.8 %)	27 (61.4 %)	
≥65 years	19 (35.8 %)	2 (22.2 %)	17 (38.6 %)	
Sex				0.222
Male	14 (26.4 %)	4 (44.4 %)	10 (22.7 %)	
Female	39 (73.6 %)	5 (55.6 %)	34 (77.3 %)	
Diabetes mellitus	13 (24.5 %)	3 (33.3 %)	10 (22.7 %)	0.672
Osteoporosis	8 (15.1 %)	1 (11.1 %)	7 (15.9 %)	1.000
Smoker	7 (13.2 %)	1 (11.1 %)	6 (13.6 %)	1.000
Garden stage				<0.001
I	30 (56.6 %)	0 (0.0 %)	30 (68.2 %)	
II	9 (17.0 %)	0 (0.0 %)	9 (20.5 %)	
III	8 (15.1 %)	3 (33.3 %)	5 (11.4 %)	
IV	6 (11.3 %)	6 (66.7 %)	0 (0.0 %)	
Interval from injury to surgery				0.715
<24 h	23 (43.4 %)	3 (33.3 %)	20 (45.5 %)	
≥24 h	30 (56.6 %)	6 (66.6 %)	24 (54.5 %)	
Follow-up period (months)	29.5 ± 19.9	30.1 ± 14.9	29.3 ± 20.9	0.914

normal femoral head uptake, whereas 38 showed cold defects (1 partial cold defect and 37 complete cold defects) on femoral heads above femoral neck fractures. All 15 patients with normal femoral head uptake healed without AVN (Fig. 2). Among the 38 patients showing cold defects on the immediate postoperative bone SPECT/CT, 9 later developed AVN (23.7 %). One patient developed Ficat stage II AVN 3 months after surgery. The other 37 patients underwent follow-up bone

SPECT/CT 2–10 months (mean 3.4 months) after surgery. Twenty-seven of thirty-seven patients showed completely normalized femoral head uptake on the follow-up bone SPECT/CT. Among these patients, 26 had no radiologic sign of AVN at the latest follow-up (Fig. 3), and 1 patient (3.7 %) exhibited Ficat stage II AVN on a radiograph 19 months after surgery, without hip pain. Another 8 of these 37 patients showed partially normalized femoral head uptake (cold defect ≤30 % of the femoral head in 4 and >30 % in 4) on the follow-up bone SPECT/CT at 2–5 months. The remaining cold defects were located on the superolateral portion of the femoral head. Three (2 with cold defects ≤30 %, 1 with >30 %) did not have AVN, and five (62.5 %) showed AVN on radiographs 11–34 months after surgery (Fig. 4). One patient developed Ficat stage II AVN without hip symptoms (cold defect ≤30 %). The other four patients developed Ficat stage III AVN (1 with ≤30 %, 3 with >30 %). Three of the four patients in Ficat stage III had hip pain, and one underwent secondary total hip replacement arthroplasty. Two of 37 patients showed persistent cold defects of the femoral head on the follow-up bone SPECT/CT at 2 months (Fig. 5); both (100 %) exhibited AVN in Ficat stages III and IV at 24 and 37 months after surgery, respectively. They experienced hip pain and underwent secondary total hip replacement arthroplasty.

The NPV of the immediate postoperative bone SPECT/CT for AVN was 100 %, whereas the PPV was 24 %. For the follow-up bone SPECT/CT at 2–10 months after surgery, the NPV was 96 %, and the PPV was 70 % when partially normalized uptake and persistent cold defects were regarded as positive findings. The association between femoral head

Fig. 1 Diagram showing the incidence of AVN of the femoral head according to postoperative bone SPECT/CT findings. The immediate postoperative bone SPECT/CT was performed within 2 weeks of surgery. The follow-up bone SPECT/CT was performed at 2–10 months after surgery. AVN avascular necrosis of the femoral head

Fig. 2 A preoperative radiograph of a 52-year-old male with left hip pain shows a left femoral neck fracture (Garden stage II) (a). The immediate postoperative bone SPECT (b) and SPECT/CT fusion (c) images at 6 days

show normal uptake of the left femoral head. The postoperative radiograph at 15 months shows the healed femoral neck with a normal appearance (d)

uptake on the follow-up postoperative bone SPECT/CT at 2–10 months and the subsequent development of AVN was significant ($P < 0.001$).

Comparison of Garden Stage and Postoperative Bone SPECT/CT Findings

The occurrence of AVN and femoral head collapse (Ficat stages III and IV) according to Garden stage and the results of bone SPECT/CT are summarized in Table 2. In patients ($n = 39$) with Garden stage I and II fractures, 15 showed normal femoral head uptake, and the other 24 showed cold defects on the immediate postoperative bone SPECT/CT but did not develop AVN later. All patients ($n = 14$) in Garden stages III and IV showed cold defects on the immediate postoperative bone SPECT/CT. Among four patients (three with Garden stage III and one with Garden stage IV) who converted to

completely normalized uptake on their follow-up bone SPECT/CT, one developed Ficat stage II AVN, but no patients developed severe AVN with femoral head collapse. However, in patients with cold defects (partially normalized uptake or persistent cold defects) remaining on the follow-up SPECT/CT, two (50 %) of four patients with Garden stage III and four (80 %) of five patients with Garden stage IV fractures later developed severe AVN with femoral head collapse. The NPV and PPV for femoral head collapse of the follow-up bone SPECT/CT were 100 % and 66.7 %, respectively.

Discussion

The results of this study demonstrated that femoral head radiotracer uptake patterns on postoperative bone SPECT/CT stratified the risk of AVN after internal fixation of a femoral

Fig. 3 A preoperative radiograph of a 65-year-old female with right hip pain shows a right femoral neck fracture (Garden stage III) (a). The immediate postoperative bone SPECT (b) and SPECT/CT fusion (c) images at 3 days show a cold defect of the right femoral head. The follow-up bone SPECT (d) and SPECT/CT fusion images (e) at 4 months show completely normalized right femoral head uptake. The postoperative radiograph at 16 months shows the healed femoral neck with a normal appearance (f)

Fig. 4 A preoperative radiograph of a 72-year-old male with right hip pain shows a right femoral neck fracture (Garden stage III) (a). The immediate postoperative bone SPECT (b) and SPECT/CT fusion (c) images at 3 days show a cold defect of the right femoral head. The follow-up bone SPECT (d) and SPECT/CT fusion (e) images at 3 months show partially normalized uptake with the remaining defect in the superior portion of the right femoral head. Postoperative radiograph at 15 months shows avascular necrosis of Ficat stage III with subchondral collapse of the right femoral head (f)

neck fracture, and the performance of bone SPECT/CT for risk assessment depended on the time point of imaging. The NPV of immediate postoperative bone SPECT/CT within 2 weeks of surgery for subsequent AVN of the femoral head was 100 %. The finding of a cold defect of the femoral head on immediate postoperative SPECT/CT within 2 weeks of surgery suggests increased risk of AVN of the femoral head, and it does not indicate necrosis within this period. The PPV was

24 %. On the follow-up bone SPECT/CT 2–5 months later, cold defects of the femoral head suggest higher risk of AVN. Notably, 62.5 % of patients with partially normalized defects and 100 % of patients with persistent cold defects of the femoral head later developed AVN.

Given that radiotracer uptake represents blood supply, normal uptake on bone SPECT/CT indicates intact vascularity, which is essential for the viability of the ipsilateral femoral

Fig. 5 A preoperative radiograph of a 59-year-old female with left hip pain shows a left femoral neck fracture (Garden stage III) (a). The immediate postoperative bone SPECT (b) and SPECT/CT fusion (c) images at 2 days show a cold defect of the left femoral head. The follow-up bone SPECT (d) and SPECT/CT fusion (e) images at 2 months show a persistent cold defect of the left femoral head. Postoperative radiograph at 37 months shows avascular necrosis of Ficat stage III with flattening of the left femoral head (f)

Table 2 The occurrence of AVN and femoral head collapse (Ficat stage III/IV) according to Garden stage and bone SPECT/CT findings

Garden stage	Immediate SPECT/CT	Follow-up SPECT/CT	No. of patients	No. of AVN	No. of femoral head collapses
I	Normal uptake	NA	10	0	0
	Cold defect	Completely normalized	19	0	0
		Partially normalized	1	0	0
II	Normal uptake	NA	5	0	0
	Cold defect	Completely normalized	4	0	0
III	Cold defect	NA	1	1	0
		Completely normalized	3	0	0
		Partially normalized	3	1	1
		Persistent cold defect	1	1	1
IV	Cold defect	Completely normalized	1	1	0
		Partially normalized	4	4	3
		Persistent cold defect	1	1	1

NA = not applicable

head after surgical fixation of a femoral neck fracture [1]. Therefore, prediction of fracture healing without AVN after internal fixation of the femoral head on the basis of normal uptake on bone SPECT/CT within 2 weeks of surgery is reasonable. An important result of this study is that the majority of cold defects of the femoral head on the immediate postoperative bone SPECT/CT within 2 weeks of surgery converted to completely or partially normalized uptake on the follow-up bone SPECT/CT. This suggests that restoration of the blood supply occurred in most of the femoral head after internal fixation of the femoral neck fracture. This finding agrees with a previous study by Kumar et al. [27], which reported that revascularization occurred in about 80 % of patients after internal fixation of a femoral neck fracture.

In our study, three of eight patients who showed partially normalized uptake on their follow-up bone SPECT/CT at postoperative 2–5 months did not show signs of AVN on radiographs. The extent of the remaining cold defect on follow-up SPECT/CT might be associated with the occurrence and severity of AVN; however, statistical analysis could not be performed because of the small numbers. Although further studies with SPECT/CT will be needed to explore the association, this finding is consistent with a previous study by Cherian et al. [11], which demonstrated that the necrotic extent of the femoral head on MRI was related to the severity of AVN. One patient developed Ficat stage II AVN despite completely normalized femoral head uptake on the follow-up bone SPECT/CT. This might have resulted from the limited spatial resolution of the SPECT scanner, although the small AVN that was obscured on SPECT is likely to have a good functional prognosis without subchondral collapse [11].

Several previous studies attempted to assess post-traumatic vascularity with bone scintigraphy for predicting AVN of the

femoral head after surgical fixation of a femoral neck fracture [16–22]. However, the reported predictive values of bone scintigraphy differed. Most of all, planar scintigraphy alone has a limited performance for evaluation of femoral head uptake compared with that of SPECT/CT [24]. Compared with bone SPECT, the complex anatomical information provided by CT in SPECT/CT is helpful, especially for differentiating between completely normalized uptake and partially normalized uptake of the femoral head, of which the latter was demonstrated to have a significant risk of developing AVN. The remaining subchondral cold defect could not be easily defined if the precise anatomical border of the femoral head was not provided by CT. Although metal implants can degrade the image quality of CT by beam-hardening artifact, SPECT images are not affected by metal implants. The performance of MRI is limited because of susceptibility artifacts in the post-operative setting. It is generally accepted that vascular damage at the time of injury leads to bone cell ischemia and subsequent cell death, followed by structural changes. Additionally, our results showed that revascularization occurs frequently and is important for the normal healing process of femoral neck fractures. We should regard a cold defect on bone SPECT/CT within 2 weeks of surgery as an avascular status rather than necrosis, even though it has a higher risk of developing AVN. In the case of cold defects of the femoral head, a subsequent bone SPECT/CT is needed approximately 2–5 months later; then, the risk of developing AVN can be judged more accurately.

The medial circumflex femoral artery, which is a major contributor of blood supply to the femoral head [14, 28–30], gives rise to the superior and inferior retinacular arteries. The superior retinacular arteries feed most of the femoral head [28]. However, because of its proximity to the superolateral

aspect of the neck, these arteries are vulnerable, especially in the case of a displaced femoral neck fracture. The territories of the inferior retinacular arteries are smaller, but have the advantage of non-proximity to the femoral neck. An intra- and extra-osseous anastomosis exists between the superior and inferior retinacular arteries, and the amount of anastomosis differs between subjects [29]. The ligamentum teres artery supplies only the perfoveolar area and does not exist in 20 % of adults [14, 28, 31]. Revascularization from the ligamentum teres artery can also occur, but it is not considered to be sufficient to cover the entire femoral head [32]. The cold defects on the bone SPECT/CT within 2 weeks could be due to disruption of the superior retinacular artery or increased intracapsular pressure, the tamponade effect of a hematoma [31]. The completely normalized uptake on the follow-up bone SPECT/CT was likely occurred by revascularization through the undamaged superior retinacular artery or a sufficient anastomosis between the superior and inferior retinacular arteries. The remaining absent uptake on the superolateral portion of the femoral head on the follow-up bone SPECT/CT implied disruption of the superior retinacular artery and an insufficient anastomosis to cover the entire femoral head.

The association between Garden stage and the occurrence of AVN was significant in our study. This finding agrees with previous studies in that a displaced femoral neck fracture is a well-known risk factor of AVN [33–35]. None of the patients with undisplaced fractures developed AVN, despite of the finding that 24 of 39 patients showed a cold defect on the immediate postoperative bone SPECT/CT. Undisplaced femoral neck fracture is likely to maintain an intact posterior retinaculum [31], on which the retinacular arteries supply the femoral head. Bone SPECT/CT may help stratify the risk of occurrence and the severity of AVN in patients with displaced fractures, as the functional prognosis of AVN primarily depends on the occurrence of subchondral collapse [11]. The time interval from injury to surgery was not significantly related to AVN of the femoral head in our study. A few previous studies reported that early surgical treatment is associated with a decreased incidence of AVN [35–37], whereas other studies found no significant relationship between the time interval and AVN [27, 38–40]. Our results show that transient perfusion defects of the femoral head followed by revascularization in the immediate postoperative period do not cause AVN. Therefore, urgent surgical attempts to restore vascularity may not be associated with a reduced incidence of AVN.

This study has several limitations. The first is the retrospective nature of the study. The follow-up bone SPECT/CT images were not obtained at the same period after surgery in all patients. Thus, it is hard to propose the optimal timing for performing follow-up SPECT/CT in the case of cold defects at the immediate postoperative SPECT/CT. Second, we set inclusion criteria of more than 1 year of clinical follow-up with radiographic evaluation. We ended regular follow-up at 1 year

for some patients at low risk of complications after surgery and educated them to return to the hospital whenever they felt uncomfortable. It is commonly accepted that AVN of the femoral head can occur up to 2 years after internal fixation of the femoral head [33]. Therefore, the incidence of AVN after internal fixation of femoral neck fractures could be underestimated. Finally, not all of the patients with internal fixation of a femoral neck fracture underwent postoperative bone SPECT/CT within 2 weeks of surgery. There could be referral bias in our study. Nevertheless, the majority (81 %, 91/112) of patients underwent postoperative bone SPECT/CT. Therefore, we can assume that referral bias had little influence on the conclusions of this study.

Conclusion

According to the time point of imaging, radiotracer uptake patterns of the femoral head on postoperative bone SPECT/CT differently indicate the risk of AVN after internal fixation of femoral neck fractures. The performance of bone SPECT/CT for risk assessment depends on the time point of imaging because revascularization occurs. On immediate postoperative bone SPECT/CT within 2 weeks of surgery, normal femoral head uptake indicates no risk of AVN. On follow-up bone SPECT/CT at 2–10 months, a partially normalized or persistent cold defect of the femoral head indicates high risk of AVN, whereas normalized uptake indicates no risk of severe AVN. Risk stratification of AVN using postoperative bone SPECT/CT may help orthopedic surgeons identify the appropriate follow-up for patients after internal fixation of a femoral neck fracture.

Compliance with Ethical Standards

Conflict of Interest Sangwon Han, Minyoung Oh, SeokhoYoon, Jinsoo Kim, Ji-Wan Kim, Jae-Suk Chang, and Jin-Sook Ryu declare that they have no conflicts of interest.

Ethical Statement All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. This study was approved by our Institutional Review Board (IRB no. 2016–0231). The Institutional Review Board waived the need to obtain informed consent. This manuscript has not been published before or is not under consideration for publication anywhere and has been approved by all co-authors.

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