In order to investigate the mechanisms of collapse in osteonecrosis of the femoral head, we examined which part of the femoral head was the key point of a collapse and whether a collapsed region was associated with the size of the necrotic lesion. Using 30 consecutive surgically removed femoral heads we retrospectively analysed whole serial cut sections, specimen photographs, specimen radiographs and histological sections.

In all of the femoral heads, collapse consistently involved a fracture at the lateral boundary of the necrotic lesion. Histologically, the fractures occurred at the junction between the thickened trabeculae of the reparative zone and the necrotic bone trabeculae. When the medial boundary of the necrotic lesion was located lateral to the fovea of the femoral head, 18 of 19 femoral heads collapsed in the subchondral region. By contrast, when the medial boundary was located medial to the fovea, collapse in the subchondral region was observed in four of 11 femoral heads (p = 0.0011). We found that collapse began at the lateral boundary of the necrotic lesion and that the size of the necrotic lesion seemed to contribute to its distribution.

Osteonecrosis of the femoral head is generally seen between the ages of 20 and 60. It often leads to destruction of the hip after collapse of the femoral head, and it accounts for more than 10% of the 500,000 total hip replacements (THRs) performed annually in the United States. When the necrotic lesion is in the weight-bearing area of the femoral head, it often collapses, causing secondary osteoarthritis with severe pain and dysfunction. Collapse, therefore, strongly influences the staging and prognosis of osteonecrosis of the femoral head.

Such collapse has been known to appear not only in the subchondral region, but also inside the necrotic lesion, as demonstrated by a previous non-linear finite-element study. There may also be changes in the proximal femur. In regard to its pathogenesis, Bullough and DiCarlo proposed the following three causes: the cumulative effect of microfractures induced by fatigue within the necrotic zone; weakness of the trabeculae in the reparative front as a result of osteoclastic activity; and focal concentration of stress at the junction between the thickened sclerotic trabeculae of the reparative zone and the necrotic trabeculae. Furthermore, Kenzora and Glömcher reported that a fracture may begin in the region of the resorbed necrotic subchondral plate at the junction of necrotic and viable bone. Both of these studies suggested that a fracture at the lateral boundary of the necrotic lesion may be an important point in collapse. To our knowledge, however, there have been no reports which have investigated the morphological characteristics of a collapsed region.

We have therefore attempted to assess which part of the femoral head was the focal point of collapse and also to examine whether a collapsed region was associated with the size of necrotic lesion.

Materials and Methods

Our study was approved by the institutional review board. A total of 30 consecutive femoral heads from 25 patients (17 men and eight women) was obtained between July 1999 and December 2009 during bipolar hemiarthroplasty for the initial treatment of stage-3A (defined as < 3 mm of collapse) or stage-3B (≥ 3 mm) osteonecrosis. The mean age at the time of the operation was 47 years (31 to 69). The cause of the osteonecrosis was considered to be the use of corticosteroids in 13 and alcohol abuse in 15 cases. In two no aetiological factor could be identified.

The femoral heads were fixed in 10% formalin solution and cut with a bone saw into serial sections 3 mm thick along the coronal plane. Ten to 12 slices were obtained from each head. The sections were decalcified in 5%
nitric acid solution, processed and embedded in paraffin, then sections 5 μm thick were prepared and stained with haematoxylin and eosin. Each femoral head was then evaluated based on the whole serial cut sections, section photographs, radiographs and histological examination.

The femoral heads were divided into two groups according to the position of the medial border of the necrotic lesion in relation to the distal end of the fovea in the central section cut through the fovea. In the small lesion group the medial boundary between the necrotic and viable zone was located lateral to the fovea of the femoral head (Fig. 1a). In the large lesion group the medial boundary was located medially beyond the fovea (Fig. 1b).

**Statistical analysis.** Univariate analysis between the groups was performed using Fisher’s exact test of the number of heads which collapsed in the subchondral region. A $p$-value $\leq 0.05$ was considered to be statistically significant.

**Results**
In all the cut sections of the 30 femoral heads the collapse involved a fracture at the lateral boundary of the necrotic lesion (Figs 2a to 2d). Histologically, the fractures occurred at the junction between the thickened trabeculae associated with appositional bone formation and the necrotic bone trabeculae (Fig. 2e). The histological features were consistent in all the heads. In two, which were both characterised by a beak-shaped intact region in the lateral area, the fractures at the lateral boundary of the necrotic lesion were not obvious either on the specimen photographs or radiographs, but were seen on the histological sections.

When the medial boundary between the necrotic and viable zone was located lateral to the fovea of the femoral head on the central cut section (small lesion group), 18 of the 19 femoral heads in this group had a collapse in the subchondral region (Figs 2a and 2b). In the remaining head, the collapse appeared deep within the necrotic lesion. By contrast, when the medial boundary was located medial to the fovea (large lesion group), collapse in the subchondral region was found in four of the 11 femoral heads in this group. In four of the other seven femoral heads, the collapse appeared in the deep necrotic region near the underlying necrotic-viable bone interface (Figs 2c and 2d). In the remaining three heads, the collapse appeared deep within the necrotic lesion. Regarding the number of heads which collapsed in the subchondral region, the two groups differed significantly (Fisher’s exact test, $p = 0.001$). Regarding age, gender and steroid/alcohol abuse, no significant differences were observed between the two groups (Table I). In two of the five bilateral cases, both femoral heads were divided into the small lesion group and had a collapse in the subchondral region. In two of the others, both heads were divided into the large lesion group. In one of the two cases, the collapsed region was similar in each hip, while in the other case, the collapsed region was different. In the remaining one bilateral case, each femoral head was divided into separate groups and the collapsed region was different.

**Discussion**
Our study has shown that a collapsed femoral head in osteonecrosis inevitably involves a fracture at the lateral boundary of the necrotic lesion. Based on the histological study of these fractures, we propose that the focal concentration of stress at the junction between the thickened trabeculae of the reparative zone and the necrotic bone trabeculae is one of the most significant causes of fracture at this lateral boundary.

The location of the lateral boundary of the necrotic lesion is well known to affect the fate of osteonecrosis of the femoral head. When the lateral boundary involves the weight-bearing portion of the femoral head, collapse of the
Figures 2a and 2b – a specimen photograph a) and radiograph b) of a femoral head, in which the medial boundary (a, white arrowhead) between the necrotic and viable zones located lateral to the fovea of the femoral head, showed collapse (b, white arrows) in the subchondral region (a, black arrowhead, the lateral boundary between the necrotic and viable zones; F, fovea). Figures 2c and 2d – a specimen photograph c) and radiograph d) of a femoral head in which the medial boundary (c, white arrowhead) located medially beyond the fovea, showed collapse (d, white arrows) in the deep necrotic region near the underlying necrotic-viable bone interface (c, black arrowhead, the lateral boundary between the necrotic and viable zones; F, fovea). Figure 2e – Photomicrograph of the area bounded by the white rectangle in Figure 2d showing fractures at the junction (arrow) between the thickened trabeculae (**) associated with appositional bone formation and the necrotic bone trabeculae (*) (Nec, necrotic zone; Rep, reparative zone; Liv, living zone; haematoxylin and eosin x 20; black bar 500 μm).

head frequently occurs. However, it rarely occurs when the lateral boundary is located within the medial portion of the femoral head. On the basis of our findings, we speculate that collapse of the necrotic femoral head may be initiated by fracturing at the lateral boundary.

In our study, collapse in the subchondral region was significantly associated with the location of the medial boundary of the necrotic lesion. However, in heads with large necrotic lesions, we often found collapse in another region, including the deep necrotic region near the underlying necrotic-viable bone interface. Min et al.¹² reviewed ten patients with subcapital fractures associated with extensive osteonecrosis of the femoral head and reported that fracture occurred at the junction between the necrotic region and the reparative interface and extended downwards through it. This may be explained by the findings of a previous three-dimensional finite-element model study, which showed that high stress was applied in the deep necrotic portion above the necrotic-viable bone interface with a large necrotic lesion. We therefore consider that the size of the necrotic lesion may be one of the influential factors in collapsed regions.

The development and progression of a collapse in osteonecrosis of the femoral head may be influenced by both the reparative reaction adjacent to the necrotic lesion and mechanical stress at the lateral boundary of the necrotic lesion. Our results may serve as basic data for future studies designed to clarify the pathomechanisms of collapse in osteonecrosis of the femoral head. There are two major weaknesses in this study. First, we were uncertain...
about the accurate onset and the duration of symptoms, especially in patients with alcohol-included osteonecrosis. We must note that femoral heads examined may represent a continuum of the natural history of osteonecrosis which may have been interrupted by an operation at different stages. Secondly, five patients (mean age 48 years (41 to 54)) had bilateral osteonecrosis; in three of these patients, the collapsed region was similar in each hip, while in the other two the pattern of collapse was different. This was probably due to different osteonecrotic lesions in both femoral heads. We therefore consider that the inclusion of these bilateral cases has little effect on the results of this study.

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Table I. Differences between age, gender and steroid/alcohol abuse between the groups

<table>
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<th></th>
<th>Small lesion group</th>
<th>Large lesion group</th>
<th>p-value*</th>
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<tr>
<td>Age (range)</td>
<td>46.7 (31 to 69)</td>
<td>48.3 (39 to 67)</td>
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<td>Gender M:F</td>
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<td>5:6</td>
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* Fisher’s exact text, a p-value < 0.05 was considered significant

References