

Regional Microdamage Accumulation in Idiopathic Osteonecrosis of the Femoral Head

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INTRODUCTION: Idiopathic osteonecrosis of the femoral head (ION) is a progressive disease that often leads to femoral head collapse, resulting in pain and functional impairment. The mechanism of femoral head collapse in ION remains poorly understood. Previous studies have suggested that stress concentration occurs at the necrotic boundary region, serving as the initiation point for collapse¹. We hypothesized that microdamage accumulation and altered bone metabolism in different regions of the necrotic femoral head contribute to the collapse mechanism. This study aimed to investigate the regional differences in bone microstructure and microdamage accumulation within ION femoral heads.

METHODS: We conducted a retrospective observational study of ten patients with ION (5 males, 5 females; mean age 48.5 ± 13.2 years) who underwent total hip arthroplasty. Histomorphometric evaluation was performed on three distinct regions of the femoral heads: the non-weight-bearing area (Non), border area (Bor), and necrotic area (Nec). Parameters assessed included trabecular bone volume fraction (BV/TV), trabecular thickness (Tb.Th), trabecular separation (Tb.Sp), trabecular number (Tb.N), crack length (Cr.Le), crack density (Cr.Dn), and crack surface density (Cr.S.Dn). Statistical analysis was performed using paired t-tests with significance set at $p < 0.05$. This study was approved by the ethics committee of the University of Kagawa (approval number 2019-212).

RESULTS: Significant regional differences were observed in bone microstructure parameters. The border area (Bor) showed significantly higher BV/TV compared to both the necrotic area (33.94 ± 8.10% vs 25.39 ± 4.80%, $p < 0.01$) and non-weight-bearing area (33.94 ± 8.10% vs 23.12 ± 9.54%, $p < 0.05$). Trabecular separation was significantly lower in the border area compared to both necrotic (48.91 ± 9.51 μm vs 62.32 ± 9.43 μm, $p < 0.01$) and non-weight-bearing areas (48.91 ± 9.51 μm vs 73.07 ± 21.61 μm, $p < 0.01$). Trabecular number was significantly higher in the border area compared to necrotic (1.38 ± 0.17 vs 1.22 ± 0.16, $p < 0.05$) and non-weight-bearing areas (1.38 ± 0.17 vs 1.10 ± 0.19, $p < 0.01$). Microdamage analysis revealed significantly higher crack density and crack surface density in the border area compared to the non-weight-bearing area (Cr.Dn: 1.17 ± 0.98 vs 0.27 ± 0.24, $p < 0.01$; Cr.S.Dn: 121.35 ± 99.60 vs 28.11 ± 29.53 μm/mm², $p < 0.01$).

DISCUSSION: This study demonstrated distinct regional differences in bone microstructure and microdamage accumulation within ION femoral heads. The border area exhibited paradoxically increased bone volume fraction and trabecular number, yet significantly higher microdamage accumulation. These findings suggest that the border area experiences intense remodeling activity and mechanical stress concentration, supporting the hypothesis that this area serves as the critical site for femoral head collapse initiation. The increased bone density in the border area may represent a compensatory response to mechanical stress, but the concurrent microdamage accumulation suggests microscopic structural failure leads to femoral head collapse.

SIGNIFICANCE: This study provides new insights into the collapse mechanism of ION by demonstrating regional variations in bone microstructure and microdamage patterns. Understanding these regional differences is crucial for developing targeted therapeutic strategies to prevent femoral head collapse and improve joint preservation outcomes in ION patients.

REFERENCES: 1. Utsunomiya T, et al. Influence of the crescent sign on collapse progression in osteonecrosis of the femoral head. Clin Orthop Relat Res. 2018;476(5):1171-1178.

Fig.1

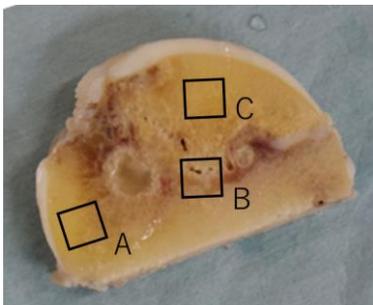


Fig.2

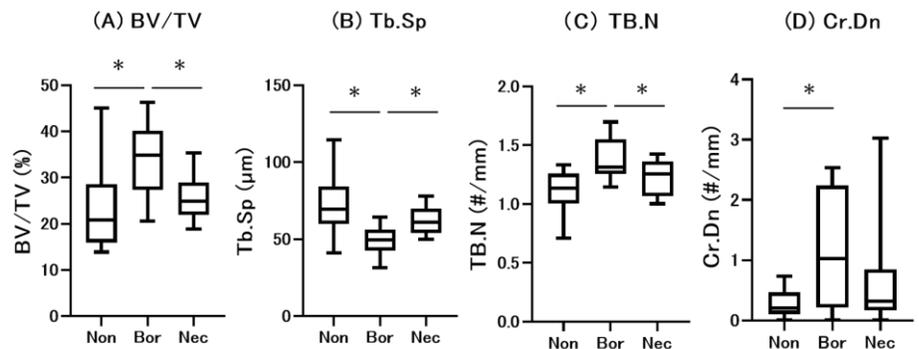


Fig.3

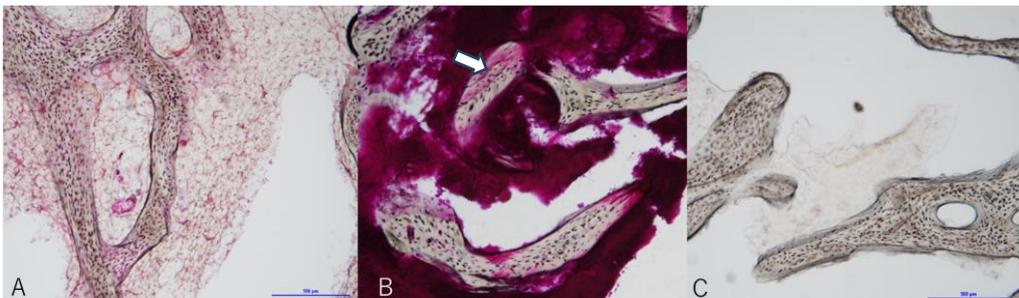


Fig.1 ION femoral head sampling regions. A: Non, B: Bor, C: Nec. 5 × 5mm squares show sampling sites.

Fig.2 Histomorphometric analysis of femoral head bone in idiopathic osteonecrosis (ION). Box plots show (A) trabecular bone volume fraction (BV/TV, %), (B) trabecular separation (Tb.Sp, μm), (C) trabecular number (Tb.N, #/mm), and (D) crack density (Cr.Dn, #/mm²). Nec: necrotic area, Non: non-weight-bearing area, Bor: border area. * $p < 0.05$ between groups.

Fig.3 Basic fuchsin staining of ION femoral head. (A) Non-weight-bearing area, (B) Border area with microcracks (white arrows), (C) Necrotic area.