

Collapse-Related Bone Changes in Osteonecrotic Femoral Heads at Multidetector CT: Comparison between Femoral Heads with Limited and Advanced Collapse



ORIGINAL ARTICLE

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ABSTRACT

Aim: To assess the frequency of bone changes in resected osteonecrotic femoral head (ONFH) specimens at multidetector computed tomography (MDCT) and compare their frequencies between ONFH with limited or advanced collapse.

Method: Fourteen ONFH were imaged using MDCT (n = 14) and microcomputed tomography (μ CT; n = 8). Preoperative staging was performed using radiographs and MRI. Coronal reformats of MDCT images of the specimens were analyzed using the grid overlay method. There were 2,933 grid boxes containing cortical bone and 10,596 containing trabecular bone. Two MSK radiologists assessed in every grid box the presence of interface-related sclerosis, cortical bone interruption, trabecular bone interruption, and trabecular bone resorption. The frequency of grid boxes with bone changes at MDCT was calculated and compared between ONFH with limited (<1.5 mm) or advanced (\geq 1.5 mm) collapse.

Results: For both readers R1 and R2, there were 1111/10596 (10.5%) and 1362/10596 (12.9%) grid boxes with interface-related bone sclerosis, 557/2933 (19%) and 413/2933 (14.1%) with cortical bone interruption, 796/10596 (7.5%) and 665/10596 (6.3%) with trabecular bone interruption, and 331/10596 (3.1%) and 595/10596 (5.6%) with trabecular bone resorption. The frequency of grid boxes with cortical interruption and trabecular bone resorption was significantly higher in ONFH with advanced than in ONFH with limited collapse. There was no significant difference in frequency of grid boxes with trabecular interruption and interface-related bone sclerosis between ONFH with advanced or limited collapse.

Conclusion: Cortical interruption and trabecular resorption, but not trabecular interruption, were more frequent in osteonecrotic femoral heads with advanced than with limited collapse.

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KEYWORDS:

osteonecrosis of the femoral head; hip; multidetector computed tomography (MDCT); epiphyseal collapse; cortical interruption; trabecular interruption; bone resorption

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INTRODUCTION

The occurrence of collapse in osteonecrotic femoral heads (ONFH) is a pivotal step towards osteoarthritis and subsequent total hip replacement. The detection of collapse relies on conventional radiography and MRI [1]. More recently, multidetector computed tomography (MDCT) has been shown to be superior to MRI and radiographs in the detection of subchondral fractures [2–4]. There is a need to better understand bone changes associated with progressive collapse. The aim of this study was to determine the frequency and topology of bone changes in a quantitative analysis performed on MDCT images of resected ONFH specimens using the grid overlay method, and to compare their frequency between femoral heads with limited or advanced collapse.

MATERIAL AND METHODS

1- PATIENTS' POPULATION

The Institutional Review Board approved the study, with the informed consent of the patients being waived because the study was performed on femoral head specimens that were resected for total hip replacement. An MSK radiologist with four years of experience collected 14 femoral head (FH) specimens with osteonecrosis (ON) from 13 patients: 8 men (46.9 years \pm 13.9) and 5 women (68.4 years \pm 16.05). These specimens were resected during hip replacement. The FH specimens were fixated in formalin. In a preliminary study on eight FH specimens, the sensitivity and specificity of *in vitro* MDCT were calculated in comparison to μ CT (see online supplemental material).

2- STAGING OF ONFH AND MEASUREMENT OF ARTICULAR SURFACE COLLAPSE

Staging of ONFH was performed on radiographs and MRI according to the ARCO classification [4]. Collapse of the articular surface was measured using the best fitting concentric circle technique [5]. The median collapse was 1.5 mm [1.1–2.1 mm, 95% CI]. There were 10 stage 3-As, 3 stage 3-Bs, and 1 stage 4 ONFH.

3- DATA ACQUISITION AND GRID OVERLYING

Fourteen resected FH specimens were scanned on a 40-row MDCT (Siemens Somatom Definition 40, Erlangen, Germany). One radiologist with four years of experience viewed the MDCT images on an image viewer with multiplanar capacity. Coronal reformats were obtained and segmented by overlaying a transparent 12 \times 12 grid. The anonymized images with the overlaid grid were uploaded on an in-house developed software that enables image analysis (Figure 1 and E1). Further details are provided in online supplemental material.

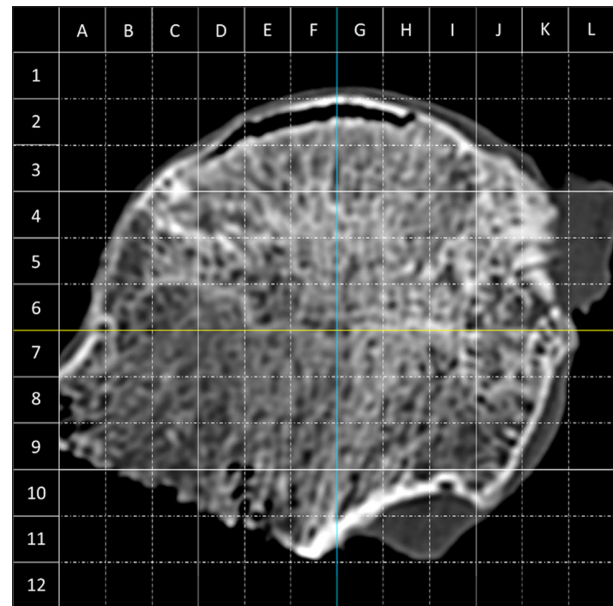


Figure 1 A 12 \times 12 transparent grid was overlaid on coronal MDCT images. Image analysis was performed in every 4 \times 4 mm grid box. As an example, grid boxes D2, D3, E2, F2, G2 and H2 contained collapse-related trabecular interruption.

4- IMAGE ANALYSIS AND LESION DEFINITION

Images were independently analyzed by an MSK radiologist with 30 years of experience (R1), and an MSK radiologist with four years of experience (R2). The reading process was performed in 4 \times 4 mm grid boxes using the grid overlay method on in-house developed software (see online supplemental material).

Bone changes at MDCT were defined as follows: interface-related trabecular sclerosis corresponded to thickened trabeculae with a band-like distribution and a concave orientation towards the articular surface. Cortical bone interruption corresponded to a focal interruption of the subchondral bone plate with or without deformity (Figure 2). Trabecular bone interruption corresponded to an interruption of two or more contiguous trabeculae, having irregular, sharp, or angular margins with or without a gas-filled cleft or a dense linear band corresponding to trabecular crushing (Figures 2–3). Trabecular bone resorption corresponded to a lucent zone devoid of mineralized content, with smooth or rounded margins (Figure 2).

Limited FH collapse was defined by the presence of a depression of the FH contours $<$ 1.5 mm, and advanced FH collapse by the presence of a depression \geq 1.5 mm.

5- STATISTICAL ANALYSIS

Data output was automatically generated on Excel sheets. Frequency of grid boxes with bone changes was compared between FH with limited and advanced collapse using Chi-squared test. Interobserver agreement was computed using Cohen's Kappa and interpreted according to the scale proposed by Altman [6]. A *p*-value

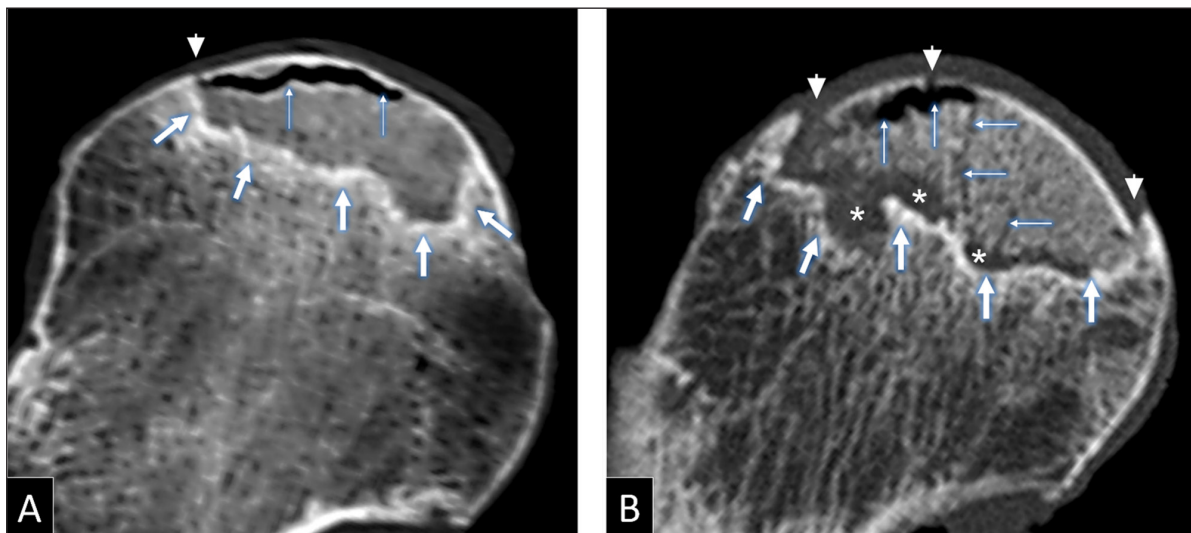


Figure 2 Coronal MDCT reformats of resected femoral head specimens of (A) a 59-year-old woman and (B) an 85-year-old woman, showing interface-related bone sclerosis (thick arrows) and collapse-related bone changes: cortical interruption (arrowheads), trabecular interruption (thin arrows) and bone resorption (asterisks in B).

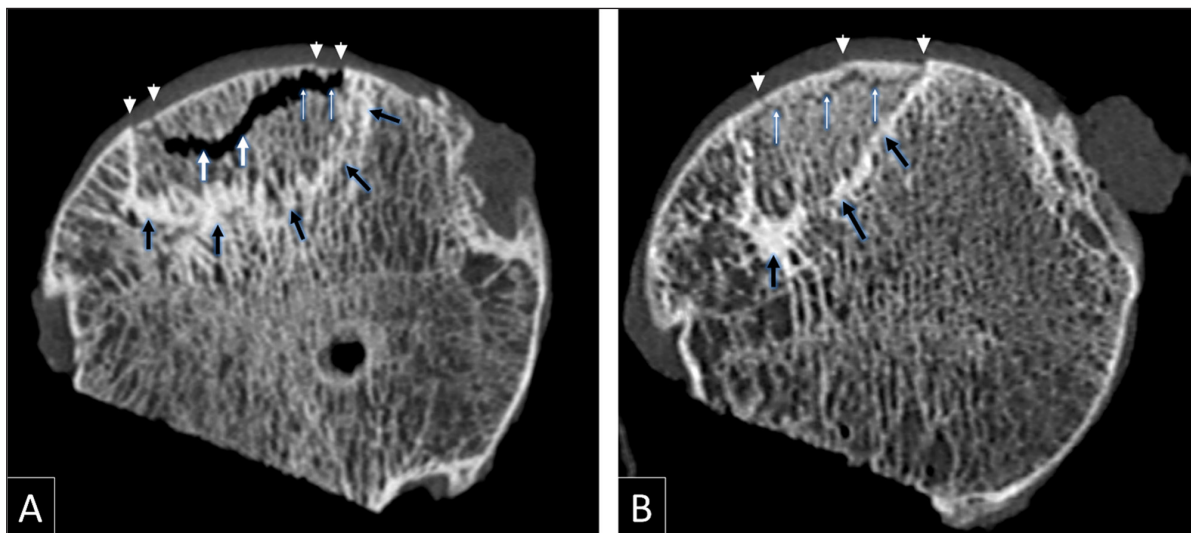


Figure 3 (A) and (B) Coronal MDCT reformats of a resected femoral head specimen in a 62-year-old man, showing collapse-related trabecular interruption in the superficial (thin white arrows) and deep layers (thick white arrows) of the trabecular bone. Also note cortical interruption (arrowheads) and interface-related bone sclerosis (black arrows).

<0.05 was regarded as statistically significant. Statistical analyses were performed by using MedCalc Statistical Software version 19.2.6 (MedCalc Software bv, Ostend, Belgium; <https://www.medcalc.org>; 2020).

RESULTS

1- FREQUENCY OF GRID BOXES WITH BONE CHANGES AT MDCT

There were 2,933 grid boxes containing cortical bone and 10596 grid boxes containing trabecular bone on the MDCT reformats. For R1, there were 557/2933 (19%) with cortical bone interruption, 796/10596 (7.5%) with trabecular bone interruption, and 331/10596 (3.1%) with trabecular bone resorption. Results for R2 are given in Table 1.

2- TOPOLOGY OF GRID BOXES WITH NECROTIC LESION AND COLLAPSE-RELATED BONE CHANGES AT MDCT

For R1, grid boxes with collapse-related bone changes (CRBC) at MDCT were more frequent in the anterior, central, and superior thirds of the FH (Table 2). Grid boxes with trabecular interruption were more frequent in the superficial (448/2621; 17.1%) than in the deep layer (348/7975; 4.4%). Grid boxes with trabecular resorption were more frequent in the deep (281/7975; 3.5%) than in the superficial layer (50/2621; 1.9%). Detailed results for R1 and R2 are provided in Table 2.

For R1, grid boxes with cortical and trabecular bone changes were more frequent within than outside the necrotic lesion ($p < 0.001$). Detailed results for R1 and R2 are provided in Table 3.

		R1	R2
Necrosis-related bone changes	Necrotic lesion	3442/10596 (32.5%)	3666/10596 (34.6%)
	Trabecular sclerosis	1111/10596 (10.5%)	1362/10596 (12.9%)
Collapse-related bone changes	Cortical interruption	557/2933 (19%)	413/2933 (14.1%)
	Trabecular interruption	796/10596 (7.5%)	665/10596 (6.3%)
	Trabecular resorption	331/10596 (3.1%)	595/10596 (5.6%)

Table 1 Frequency of grid boxes with cortical and trabecular bone changes on coronal MDCT reformats of 14 femoral head specimens. R1 and R2 represent two readers.

3- COMPARISON OF FREQUENCY OF GRID BOXES WITH NECROTIC LESIONS AND CRBC AT MDCT BETWEEN LIMITED AND ADVANCE COLLAPSE

For R1, grid boxes with cortical interruption were more frequent in FH with collapse ≥ 1.5 mm (20.49%) than in FH with collapse < 1.5 mm (17.02%) ($p = 0.018$). There was no statistical difference in the frequency of grid boxes with trabecular interruption between FH with collapse ≥ 1.5 mm (7.13%) than < 1.5 mm (8%) ($p = 0.094$). Grid boxes with trabecular resorption were more frequent in FH with collapse ≥ 1.5 mm (3.88%) than < 1.5 mm (2.15%) ($p < 0.001$). Detailed results for R1 and R2 are provided in [Table 4](#).

DISCUSSION

In the current study, we assessed bone changes in ONFH specimens using MDCT and found that grid boxes with necrotic lesion and CRBC predominated in the anterior, central, and superior parts of ONFH specimens. We also found that grid boxes with cortical interruption and trabecular bone resorption were more frequent in femoral heads with advanced collapse than in those with limited collapse, with no difference in frequency of bone interruption according to the degree of collapse. These observations suggest that progression of collapse could be more associated with the development of cortical bone fracture and bone resorption than with trabecular bone interruption.

First, the observation that trabecular bone interruption predominated in the superficial layer of the necrotic lesion could be explained by the concentration of mechanical stress on the surface or by its association with cortical interruption [7–11]. The predominance of trabecular bone resorption in the deep regions of the necrotic lesions is associated with the repair process

that include increased bone remodeling in vascularized regions surrounding and invading the lesion [11, 12].

Second, the fact that cortical bone interruption was more frequent in ONFH with advanced than with limited collapse is associated with marked deformity of the subchondral bone plate that results from collapse. The observation that bone resorption was more frequent with more advanced collapse suggests that resorption could develop during progressive failure of the FH and is not associated with early fracture [9, 13].

Third, the lack of difference in frequency of trabecular interruption according to the degree of collapse could contradict the general idea that links trabecular fracture with collapse. Trabecular fracture formation could differ from collapse, similar to what is observed in rocks [14]. In ONFH, stress distribution is altered by progressive collapse and development of trabecular fracture can be dissociated from that of cortical fracture [15]. The hypothesis that progression of collapse is associated with bone resorption and cortical fracture but not with trabecular bone fracture deserves further analysis.

Our study has many limitations. In addition to a limited number of specimens, histological confirmation of the findings was not performed. Since μ CT can accurately detect cortical and trabecular microfractures in comparison with histology [16, 17], we obtained μ CT examinations in eight specimens and demonstrated that MDCT had a high specificity to detect cortical fractures, trabecular fracture, resorption, and sclerosis in comparison with μ CT (see supplemental material).

In conclusion, cortical and trabecular bone interruption and trabecular bone resorption are found in collapsed ONFH and their distribution parallels that of the necrotic lesions. Grid boxes with cortical bone interruption and trabecular bone resorption but not with trabecular bone interruption are more frequent in ONFH with advanced than with limited collapse.

Table 2 Frequency of grid boxes with CRBC and with necrotic lesion in different thirds regions of the FH in the coronal plane on MDCT reformats.

The denominators represent the total number of grid boxes in every region. (p¹) Anterior versus Middle; (p²) Anterior versus Posterior; (p³) Middle versus Posterior; (p⁴) = Medial versus Central; (p⁵) = Medial versus Lateral; (p⁶) = Central versus Lateral. (p⁷) = Superior versus Inferior; (p⁸) = Middle versus inferior.

	ANTERO-POSTERIOR DIRECTION			MEDIO-LATERAL DIRECTION			CRANIO-CAUDAL DIRECTION			RADIAL DIRECTION					
	ANT	MID	POST	P	MED	CENT	LAT	P	SUP	MID	INF	P	SUPERFICIAL	DEEP	P
R1 Necrotic Lesion*	782/2159 (36.2%)	1345/4354 (30.9%)	623/2419 (25.8%)	P ¹ < 0.001	681/2427 (28.1%)	1582/4345 (36.4%)	487/2160 (22.5%)	P ² < 0.001	1713/2273 (75.4%)	1030/4632 (22.2%)	7/2027 (0.3%)	P ⁷ < 0.001	823/2232 (36.9%)	1927/6700 (28.8%)	P < 0.001
				P ² < 0.001				P ³ < 0.001				P ⁸ < 0.001			
				P ³ < 0.001								P ⁹ < 0.001			
Trabecular sclerosis	324/2562 (12.6%)	509/5134 (9.9%)	278/2900 (9.6%)	P ¹ < 0.001	273/2867 (9.5%)	587/5125 (11.45%)	251/2604 (9.6%)	P ² < 0.001	422/2671 (15.8%)	650/5447 (11.9%)	39/2478 (1.6%)	P ⁷ < 0.001	203/2621 (7.7%)	908/7975 (11.4%)	P < 0.001
				P ² < 0.001				P ³ = 0.664				P ⁸ < 0.001			
				P ³ = 0.664								P ⁹ < 0.001			
Cortical interruption	213/830 (25.7%)	236/1199 (19.7%)	108/904 (11.9%)	P ¹ = 0.001	131/1357 (6.7%)	252/846 (29.8%)	174/730 (23.8%)	P ² < 0.001	486/1388 (35%)	71/941 (7.5%)	0/604 (0%)	P ⁷ < 0.001	NA	NA	
				P ² < 0.001				P ³ < 0.001				P ⁸ < 0.001			
				P ³ < 0.001								P ⁹ < 0.001			
Trabecular interruption	243/2562 (9.5%)	404/5134 (7.9%)	149/2900 (5.1%)	P ¹ = 0.02	160/2867 (5.6%)	448/5125 (8.7%)	188/2604 (7.2%)	P ² < 0.001	693/2671 (25.9%)	99/5447 (1.8%)	4/2478 (0.2%)	P ⁷ < 0.001	448/2621 (17.1%)	348/7975 (4.4%)	P < 0.001
				P ² < 0.001				P ³ < 0.001				P ⁸ < 0.001			
				P ³ < 0.001								P ⁹ < 0.001			
Trabecular resorption	162/2562 (6.3%)	125/5134 (2.4%)	44/2900 (1.5%)	P ¹ < 0.001	59/2867 (2.1%)	204/5125 (4%)	68/2604 (2.6%)	P ² < 0.001	171/2671 (6.4%)	143/5447 (2.6%)	17/2478 (0.7%)	P ⁷ < 0.001	50/2621 (1.9%)	281/7975 (3.5%)	P < 0.001
				P ² < 0.001				P ³ = 0.007				P ⁸ < 0.001			
				P ³ = 0.007								P ⁹ < 0.001			
R2 Necrotic Lesion*	884/2159 (40.9%)	1323/4354 (30.4%)	607/2419 (25.1%)	P ¹ < 0.001	685/2427 (28.2%)	1585/4345 (36.5%)	544/2160 (25.2%)	P ² < 0.001	1766/2273 (77.7%)	1036/4632 (22.4%)	12/2027 (0.6%)	P ⁷ < 0.001	897/2232 (40.2%)	1917/6700 (28.6%)	P < 0.001
				P ² < 0.001				P ³ < 0.001				P ⁸ < 0.001			
				P ³ < 0.001								P ⁹ < 0.001			
Trabecular sclerosis	421/2562 (16.4%)	616/5134 (12%)	325/2900 (11.2%)	P ¹ < 0.001	332/2867 (11.6%)	662/5125 (12.9%)	368/2604 (14.1%)	P ² < 0.001	590/2671 (22.1%)	732/5447 (13.4%)	40/2478 (1.6%)	P ⁷ < 0.001	317/2621 (12.1%)	1045/7975 (13.1%)	P = 0.185
				P ² < 0.001				P ³ = 0.284				P ⁸ < 0.001			
				P ³ = 0.284								P ⁹ < 0.001			
Cortical interruption	168/830 (20.2%)	179/1199 (14.9%)	66/904 (7.3%)	P ¹ = 0.002	112/1357 (8.3%)	186/846 (22%)	115/730 (15.75%)	P ² < 0.001	350/1388 (25.2%)	60/941 (6.4%)	3/604 (0.5%)	P ⁷ < 0.001	NA	NA	
				P ² < 0.001				P ³ < 0.001				P ⁸ < 0.001			
				P ³ < 0.001								P ⁹ < 0.001			
Trabecular interruption	228/2562 (8.9%)	306/5134 (6%)	131/2900 (4.5%)	P ¹ < 0.001	108/2867 (3.8%)	432/5125 (8.4%)	125/2604 (4.8%)	P ² < 0.001	582/2671 (21.8%)	83/5447 (1.5%)	0/2478 (0%)	P ⁷ < 0.001	389/2621 (14.8%)	276/7975 (3.5%)	P < 0.001
				P ² < 0.001				P ³ = 0.004				P ⁸ < 0.001			
				P ³ = 0.004								P ⁹ < 0.001			
Trabecular resorption	243/2562 (9.5%)	248/5134 (4.8%)	104/2900 (3.6%)	P ¹ < 0.001	116/2867 (4.1%)	334/5125 (6.5%)	145/2604 (5.6%)	P ² < 0.001	353/2671 (13.2%)	238/5447 (4.4%)	4/2478 (0.2%)	P ⁷ < 0.001	110/2621 (4.2%)	485/7975 (6.1%)	P < 0.001
				P ² < 0.001				P ³ = 0.011				P ⁸ < 0.001			
				P ³ = 0.011								P ⁹ < 0.001			

*Frequency of grid boxes containing the necrotic lesion was calculated in 12 instead of 14 ONFH because the interface was only partially visible.

	COLLAPSE-RELATED BONE CHANGES	OUTSIDE NECROTIC LESION	WITHIN NECROTIC LESION	P VALUE
R1	Cortical bone interruption	42/1507 (2.8%)	415/979 (42.4%)	p < 0.001
	Trabecular bone interruption	18/6182 (0.3%)	648/2750 (23.6%)	p < 0.001
	Trabecular bone resorption	20/6182 (0.3%)	246/2750 (8.9%)	p < 0.001
R2	Cortical bone interruption	24/1507 (1.6%)	315/979 (32.2%)	p < 0.001
	Trabecular bone interruption	3/6118 (0.05%)	544/2814 (19.3%)	p < 0.001
	Trabecular bone resorption	3/6118 (0.05%)	519/2814 (18.4%)	p < 0.001

Table 3 Comparison of frequency of grid boxes with CRBC on coronal MDCT reformats within or outside the osteonecrotic lesions*.

* Frequency of grid boxes containing the necrotic lesion was calculated in 12 instead of 14 ONFH because the interface was only partially visible.

FREQUENCY OF GRID BOXES CONTAINING	R1			R2		
	COLLAPSE <1.5 mm	COLLAPSE ≥1.5 mm	P VALUE	COLLAPSE <1.5 mm	COLLAPSE ≥1.5 mm	P VALUE
Necrotic lesion	1481/4610 (32.13%)	1961/5986 (32.76%)	P = 0.503	1460/4610 (31.67%)	2206/5986 (36.85%)	p < 0.001
Interface-related Trabecular sclerosis	499/4610 (10.82%)	612/5986 (10.22%)	P = 0.318	577/4610 (12.51%)	785/5986 (13.11%)	P = 0.360
Cortical bone interruption	216/1269 (17.02%)	341/1664 (20.49%)	P = 0.018	121/1269 (9.54%)	292/1664 (17.55%)	p < 0.001
Trabecular bone interruption	369/4610 (8%)	427/5986 (7.13%)	P = 0.094	299/4610 (6.49%)	366/5986 (6.11%)	P = 0.443
Trabecular bone resorption	99/4610 (2.15%)	232/5986 (3.88%)	p < 0.001	214/4610 (4.64%)	381/5986 (6.36%)	p < 0.001

Table 4 Comparison of frequency of grid boxes with necrotic lesions and CRBC at MDCT between ONFH with limited and advanced collapse.

ABBREVIATIONS

ARCO: Association Research Circulation Osseous
 CRBC: collapse-related bone changes
 FH: femoral head
 MDCT: multidetector computed tomography
 ON: osteonecrosis
 ONFH: osteonecrotic femoral heads
 μCT: Microcomputed tomography

COMPETING INTERESTS

The authors have no competing interests to declare.

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