

Compartment-Specific Elemental Distribution in Osteonecrosis of the Femoral Head: A Paired Analysis from the Katanga Copperbelt

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Research Article

Keywords: Osteonecrosis of the femoral head, Trace elements, Magnesium, Bone tissue, Femoral head, Inductively coupled plasma optical emission spectrometry

Posted Date: October 8th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11157617/v1>

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Additional Declarations: No competing interests reported.

Abstract

Background

Bone stores mineral and trace elements, but their distribution within the structural compartments of the femoral head remains poorly understood. This study assessed whether elemental concentrations differ between necrotic, cancellous, and compact bone within the same femoral head affected by osteonecrosis.

Methods

Thirty-five femoral heads from 34 patients undergoing total hip arthroplasty for osteonecrosis were analyzed. Paired samples of necrotic, cancellous, and compact bone were collected from each femoral head. Arsenic, cadmium, cobalt, chromium, copper, magnesium, nickel, lead, and zinc were quantified in dry bone using inductively coupled plasma optical emission spectrometry. Concentrations were compared using the Friedman test, with correction for multiple comparisons.

Results

Magnesium showed the strongest compartment-specific variation. Median concentrations were 1164 µg/g in necrotic bone, 1348 µg/g in cancellous bone, and 1492 µg/g in compact bone ($p = 0.000245$; adjusted $q = 0.0022$). Magnesium concentrations were significantly lower in necrotic bone than in cancellous and compact bone. Lead concentrations were also higher in necrotic than in compact bone, but this difference was no longer significant after correction for multiple testing. No significant compartment-specific differences were observed for the other elements.

Conclusion

Elemental distribution within the osteonecrotic femoral head appears to be compartment-specific. The lower magnesium concentration in necrotic bone suggests a local disturbance in mineral homeostasis associated with osteonecrotic tissue changes and bone remodelling.

Introduction

Osteonecrosis of the femoral head (ONFH) is a progressive and disabling disorder characterized by compromised blood supply to the femoral head, leading to osteocyte death, impaired bone remodelling, structural weakening, and, in advanced stages, collapse of the femoral head. Although several traumatic and non-traumatic risk factors are well established, the pathogenesis of ONFH remains multifactorial and incompletely understood [1]. In mining regions such as the Katanga Copperbelt in the Democratic Republic of the Congo, chronic environmental and occupational exposure to metallic elements may represent an additional factor of interest in understanding the biological environment associated with ONFH.

In a previous study conducted in the same mining region, we found that increased bone concentrations of Lead and Cobalt were significantly associated with ONFH, with elevated Pb remaining independently associated after adjustment for age [2]. These findings suggested a possible relationship between chronic skeletal accumulation of selected metallic elements and ONFH. However, that study assessed the overall elemental burden of bone specimens and did not examine whether these elements were uniformly distributed within the affected femoral head. The present study therefore addresses a distinct but complementary question by focusing on the spatial distribution of elements across paired bone compartments within the same osteonecrotic femoral head.

Bone is a heterogeneous tissue composed of structurally and metabolically distinct compartments, and elemental concentrations may vary according to bone type and local biological conditions. Previous work has shown differences in trace-element concentrations between cortical and trabecular bone [3]. In the setting of ONFH, where ischemic injury, bone cell death, resorption, and repair coexist within the same femoral head, these physiological differences may be further modified by local pathological processes. This raises an important question: does necrotic bone exhibit a distinct elemental profile compared with adjacent cancellous and compact bone?

We hypothesized that elemental concentrations are not uniformly distributed within the osteonecrotic femoral head and that necrotic bone may exhibit a distinct elemental profile compared with adjacent structurally preserved bone. The aim of the present study was therefore to compare the concentrations of arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), magnesium (Mg), nickel (Ni), lead (Pb), and zinc (Zn) across three paired compartments from the same femoral head: necrotic bone, cancellous bone, and compact bone. By using a within-specimen paired approach, we sought to identify local elemental differences that could provide further insight into the biological changes associated with ONFH.

Methods

Study design and bone sampling

This compartmental analytical study included femoral heads obtained from patients undergoing total hip arthroplasty (Fig. 1) for ONFH (Fig. 2) in the Katanga Copperbelt, southeastern Democratic Republic of the Congo. Immediately after surgical extraction, each femoral head was placed in a sterile, additive-free polyethylene container and stored at -20°C until laboratory analysis.

Three anatomically distinct bone specimens were obtained from each femoral head and analyzed as paired samples. Necrotic bone (N) was identified macroscopically by its devitalized appearance and was sampled from the affected subchondral region, including areas of structural collapse when present. Cancellous bone (S) was obtained from macroscopically preserved trabecular bone located away from the necrotic area. Compact bone (D) was sampled from the cortical bone of the femoral head specimen (Fig. 3).

Only femoral heads with complete elemental measurements from all three compartments were included in the analysis. A total of 35 femoral heads from 34 patients were analyzed, with one patient contributing bilateral specimens.

Sample preparation

Bone specimens from each compartment were processed separately to minimize the risk of cross-contamination. Samples were dried in a BINDER laboratory oven at 105°C for approximately 4 hours until a constant weight was achieved. Each dried specimen was then ground into a homogeneous powder using a ceramic mortar and pestle. Metallic instruments were avoided during grinding to minimize the risk of exogenous metal contamination. The grinding equipment was thoroughly cleaned with ultrapure distilled water between samples, and all sample containers were acid-rinsed before use.

For each specimen, exactly 0.3500 g of dry bone powder was weighed using a Mettler Toledo analytical balance. Wet digestion was performed using freshly prepared aqua regia consisting of three volumes of hydrochloric acid (HCl, 37%) and one volume of nitric acid (HNO₃, 65%). Samples were digested in a laboratory digester for 4 hours at 200°C. After digestion and cooling, the samples were diluted with ultrapure distilled water to a final volume of 40 mL and filtered through Whatman filter paper before elemental analysis. Each necrotic, cancellous, and compact bone specimen was processed independently throughout sample preparation and digestion to prevent cross-contamination between bone compartments.

Trace element analysis

Bone samples were digested using a PG Instrument 8210 digestion system. Elemental analyses were performed at the laboratory of the Office Congolais de Contrôle (OCC), Lubumbashi, Democratic Republic of the Congo, which is accredited by the Southern African Development Community Accreditation Service (SADCAS) in accordance with ISO/IEC 17025:2017 (*accreditation No. TEST-5 0102*). Elemental concentrations were determined by inductively coupled plasma optical emission spectrometry (ICP-OES) using an Optima 8300 spectrometer (PerkinElmer®, USA). Nine elements were analyzed: As, Cd, Co, Cr, Cu, Mg, Ni, Pb, and Zn.

Instrument calibration was performed using multi-element standard solutions at six concentration levels: 0.1, 0.5, 2, 3, 4, and 5 mg/L. Analytical performance was assessed according to the OCC laboratory validation procedure using element-specific limits of detection (LOD), limits of quantification (LOQ), repeatability, and intermediate precision. For the nine elements included in this study, LODs ranged from 0.27 to 5.70 µg/L, while LOQs ranged from 0.90 to 19.00 µg/L. Coefficients of variation for repeatability (CVr) ranged from 1.21% to 8.17%, and those for intermediate precision (CVFi) ranged from 2.37% to 15.62%. Element-specific analytical wavelengths and validation parameters are provided in Supplementary Table 1.

Each bone sample was analyzed in duplicate, and elemental concentrations were expressed as micrograms per gram of dry bone weight ($\mu\text{g/g}$).

Statistical analysis

Element concentrations were summarized using medians and interquartile ranges (IQR). Differences among N, S, and D bone compartments were assessed using the Friedman test, with Kendall's W used to estimate effect size. P values from the global Friedman tests were adjusted for multiple comparisons using the Benjamini–Hochberg false discovery rate (FDR) procedure. For elements with a global Friedman p value < 0.05, pairwise comparisons between N-S, N-D, and S-D were performed using the Wilcoxon signed-rank test with Holm correction. Sensitivity analyses were conducted after excluding the specimen with an atypical near-zero multielement profile and after retaining only one femoral head from the patient with bilateral specimens. All tests were two-sided. Statistical significance was set at $p < 0.05$ and $q < 0.05$ after FDR correction.

Ethical considerations

The study was approved by the Medical Ethics Committee of the University of Lubumbashi (reference: UNILU/CEM/131/2022) and was conducted in accordance with the principles of the Declaration of Helsinki. Written informed consent was obtained from all participants before inclusion in the study. Bone specimens were obtained from tissue removed as part of routine therapeutic total hip arthroplasty, with no additional invasive procedure performed for research purposes.

Results

Study population

The analysis included 35 femoral heads obtained from 34 patients with osteonecrosis of the femoral head, all of whom had complete paired measurements from necrotic, cancellous, and compact bone compartments. One patient contributed bilateral femoral heads. The mean age of the patients was 50.7 ± 15.3 years. Twenty-five patients were men (73.5%) and nine were women (26.5%). Sixteen patients resided in Lubumbashi, while 18 lived in other locations within the Katanga Copperbelt, mainly Kolwezi, Kambove, and Kasumbalesa (see Table 2).

Table 2
Characteristics of the study population

Characteristic	Value
Patients, n	34
Femoral heads analyzed, n	35
Age, years, mean $\pm$ SD	50.7 $\pm$ 15.3
Male sex, n (%)	25 (73.5)
Female sex, n (%)	9 (26.5)
Residence in Lubumbashi, n (%)	16 (47.1)
Residence elsewhere in the Katanga Copperbelt, n (%)	18 (52.9)

SD =standard deviation.

Note

Thirty-five femoral heads were obtained from 34 patients because one patient contributed bilateral specimens.

Compartment-specific elemental distribution

The concentrations of the nine analyzed elements according to bone compartment are presented in Table 3. Magnesium showed the strongest and most consistent compartment-specific variation. Median Mg concentrations were 1164 $\mu\text{g/g}$ (IQR 952–1344) in necrotic bone, 1348 $\mu\text{g/g}$ (IQR 1143–1487) in cancellous bone, and 1492 $\mu\text{g/g}$ (IQR 1194–1585) in compact bone. The overall compartmental difference was statistically significant (Friedman $\chi^2 = 16.629$, $p = 0.000245$) and remained significant after correction for multiple testing (FDR-adjusted $q = 0.0022$). Kendall's W was 0.238, indicating a measurable compartmental effect.

Post-hoc analyses showed significantly lower Mg concentrations in necrotic bone than in cancellous bone (Holm-adjusted $p = 0.0029$) and compact bone (Holm-adjusted $p = 0.0029$). The difference between cancellous and compact bone was not statistically significant (Holm-adjusted $p = 0.108$). The paired distribution of Mg concentrations across the three compartments is shown in Fig. 4

Lead showed a weaker compartment-specific pattern. Median Pb concentrations were 0.841 $\mu\text{g/g}$ (IQR 0.288–2.153) in necrotic bone, 0.827 $\mu\text{g/g}$ (IQR 0.247–1.332) in cancellous bone, and 0.544 $\mu\text{g/g}$ (IQR 0.011–1.175) in compact bone. The global Friedman test was significant before correction for multiple testing ($\chi^2 = 8.311$, $p = 0.0157$), but the association did not remain statistically significant after FDR correction ($q = 0.0705$).

Exploratory pairwise analysis showed a higher Pb concentration in necrotic than in compact bone (Holm-adjusted $p = 0.0406$), whereas the necrotic–cancellous and cancellous–compact comparisons were not statistically significant. Because the global Pb association did not remain significant after FDR correction, these pairwise findings were considered exploratory. The distribution of Pb concentrations across compartments is shown in Fig. 5

No statistically significant compartment-specific differences were observed for As, Cd, Co, Cr, Cu, Ni, or Zn after correction for multiple testing.

Table 3
Compartment-specific concentrations of selected elements in femoral heads with osteonecrosis

Element	Necrotic bone, median (IQR)	Cancellous bone, median (IQR)	Compact bone, median (IQR)	Friedman χ^2	p value	FDR-adjusted q value	Kendall's W
As	0.935(0.647–1.158)	1.002 (0.744–1.214)	0.841 (0.675–1.076)	0.400	0.8187	0.8920	0.006
Cd	0.000(0.000–0.019)	0.000 (0.000–0.017)	0.000 (0.000–0.032)	0.900	0.6376	0.8198	0.013
Co	0.741(0.512–1.212)	0.784 (0.473–1.038)	0.686 (0.470–0.991)	2.057	0.3575	0.6435	0.029
Cr	0.953(0.775–1.131)	0.886 (0.624–1.131)	0.902 (0.803–1.316)	0.229	0.8920	0.8920	0.003
Cu	1.902(1.110–3.629)	1.779 (0.863–3.965)	1.221 (0.524–1.892)	3.554	0.1691	0.5074	0.051
Mg	1164 (952–1344)	1348 (1143–1487)	1492 (1194–1585)	16.629	0.000245	0.0022	0.238
Ni	0.298(0.190–0.454)	0.243 (0.166–0.394)	0.293 (0.167–0.474)	1.600	0.4493	0.6740	0.023
Pb	0.841(0.288–2.153)	0.827 (0.247–1.332)	0.544 (0.011–1.175)	8.311	0.0157	0.0705	0.119
Zn	55.29(45.23–62.24)	56.88 (51.56–63.91)	54.53 (49.70–58.62)	2.800	0.2466	0.5548	0.040

IQR, interquartile range; FDR, false discovery rate.

Discussion

The compartment-specific Mg finding was the most consistent result of the present study. Magnesium concentrations progressively increased from necrotic to cancellous and compact bone, and the difference remained significant after FDR correction and sensitivity analyses. This finding is particularly noteworthy in light of the early observations of Milachowski, who examined mineral and trace-element concentrations in different regions of femoral heads affected by idiopathic ischemic necrosis [4]. His sampling scheme distinguished the necrotic area, apparently preserved subchondral bone, cancellous bone, and cortical bone, closely resembling the compartmental concept used in the present study. In osteonecrotic femoral heads, Milachowski reported Mg concentrations of approximately 1409 ± 385 mg/kg in the necrotic region, 1542 ± 337 mg/kg in cancellous bone, and 1651 ± 568 mg/kg in cortical bone [4]. Although that study primarily compared ONFH specimens with normal and osteoarthritic bone rather than formally testing paired intrafemoral differences, the numerically lowest Mg concentration in the necrotic region is remarkably consistent with the spatial pattern observed in our study. Our findings therefore extend these historical observations by demonstrating, within the same femoral heads, a statistically robust depletion of Mg in necrotic bone compared with adjacent cancellous and compact bone.

The biological interpretation of this gradient requires caution. Magnesium is an important component of skeletal mineral homeostasis and contributes to bone mineralization and remodeling through effects on osteoblast and osteoclast activity [5,6]. The observation that Mg concentrations may vary with local skeletal pathology is also supported by more recent human data. Dąbrowski et al. reported significantly higher Mg concentrations in femoral heads with severe radiographic osteoarthritis than in those with milder disease, whereas no corresponding difference was observed in the femoral neck [7]. In addition, Brodziak-Dopierała et al. demonstrated substantial variation in elemental concentrations among different tissues and structural components of the hip joint, supporting the concept that elemental composition is influenced by local bone architecture and metabolic activity [8]. Taken together, these findings suggest that bone Mg concentration may reflect not only systemic mineral status but also local tissue structure and remodeling conditions. The lower Mg concentration observed in necrotic bone in our study may therefore reflect altered mineralization, increased resorption, impaired bone formation, or redistribution of mineral components during ischemic injury and subsequent repair. However, because our study is cross-sectional and includes femoral heads removed at an advanced stage of ONFH, it cannot determine whether local Mg depletion precedes osteonecrosis or develops as a consequence of tissue necrosis and remodeling.

The Pb findings should be interpreted more cautiously than those for Mg. In our previous study, increased skeletal Pb concentrations were strongly associated with ONFH, and elevated Pb remained independently associated with the disease after adjustment for age [2]. In the present compartmental analysis, Pb concentrations were highest in necrotic bone and lowest in compact bone. Although the global Friedman test was significant before correction and the exploratory necrotic–compact comparison also reached nominal significance, the overall association did not remain significant after FDR correction. The present findings should therefore be considered suggestive rather than confirmatory evidence of preferential Pb localization within necrotic bone.

Nevertheless, the observed pattern is consistent with earlier observations. Milachowski reported higher Pb concentrations in femoral heads affected by idiopathic ischemic necrosis than in osteoarthritic or normal femoral heads and also observed elevated Pb concentrations within the necrotic region itself [4]. In that study, Pb concentrations were approximately 4.67 ± 3.41 ppm in necrotic bone compared with 1.75 ± 0.56 ppm in normal bone [4]. More broadly, Pb has a strong affinity for mineralized tissues and the adult skeleton represents its principal long-term storage compartment [9]. Lanocha et al., studying human femoral heads obtained during hip arthroplasty, emphasized that bone Pb reflects cumulative exposure and may vary according to bone structure and individual characteristics [9]. These observations support the biological plausibility of heterogeneous Pb distribution within the femoral head.

However, the mechanisms underlying the relatively higher Pb concentration observed in necrotic bone remain uncertain. Local accumulation could theoretically reflect pre-existing deposition, but redistribution during bone resorption and remodeling is an equally plausible explanation. This distinction is particularly important in ONFH, where ischemic injury, necrosis, resorption, and reparative remodeling occur simultaneously within different regions of the femoral head. Our data therefore do not establish that local Pb accumulation causes osteonecrosis. Rather, they suggest that the relationship between Pb and ONFH may involve both overall skeletal burden and local changes in bone turnover, a hypothesis that should be tested in larger studies integrating elemental measurements with histological and remodeling markers.

The absence of a significant compartment-specific gradient for Co is also informative. In our previous study, increased bone Co concentrations were associated with ONFH [2], whereas in the present paired analysis Co concentrations did not differ significantly between necrotic, cancellous, and compact bone. This apparent discrepancy may reflect the different questions addressed by the two studies. The previous analysis evaluated whether the overall skeletal burden of Co differed according to disease status, while the present study examined whether Co was preferentially distributed within specific regions of the same osteonecrotic femoral head. The lack of a local gradient therefore does not exclude increased overall skeletal accumulation. Rather, it may suggest that Co deposition, when present, is more diffusely distributed throughout the femoral head than the compartment-specific changes observed for Mg.

Previous studies of human hip tissue also indicate that elemental distribution is highly element-dependent. Brodziak-Dopierała et al. demonstrated substantial differences in the concentrations of several elements among cancellous bone, cortical bone, cartilage, and other tissues of the hip joint [8], whereas Lanocha et al. found that many measured elements did not differ significantly between spongy bone and cartilage with adjacent compact bone [9]. Milachowski similarly reported heterogeneous patterns among individual elements in osteonecrotic femoral heads: Mg and Cu were reduced, whereas Pb and Ni were increased, while some other elements showed no consistent regional difference [4]. These observations reinforce the concept that elemental behavior within bone cannot be generalized from one element to another.

The absence of significant compartmental differences for As, Cd, Cr, Cu, Ni, and Zn in our study should therefore not be interpreted as evidence that these elements have no biological relevance in ONFH. Rather, within this sample, they did not demonstrate a reproducible spatial pattern after correction for multiple

testing. This distinction is particularly important for Cd, for which a substantial proportion of analytical values were close to or below the analytical detection range and were represented as zero in the dataset. Interpretation of Cd and other low-concentration elements should therefore remain cautious until element-specific limits of detection and quantification from the analytical laboratory are incorporated into the final analysis.

A major strength of the present study is its paired within-specimen design. Each femoral head provided necrotic, cancellous, and compact bone samples, allowing every specimen to serve as its own internal reference. This approach substantially reduces the influence of interindividual variability in age, environmental exposure, metabolism, lifestyle, and other host-related factors that may affect bone elemental concentrations. Previous studies have demonstrated that elemental concentrations may differ between structural components of the hip joint [8,9], supporting the importance of accounting for anatomical compartment when interpreting bone elemental measurements.

A second strength is the direct analysis of human bone tissue rather than relying solely on circulating biomarkers. Because bone represents a long-term reservoir for several elements, direct tissue measurement provides information on skeletal elemental composition that cannot be fully captured by blood or urine measurements. The study also incorporated a statistical strategy designed to limit false-positive findings, including paired non-parametric testing, estimation of effect size with Kendall's W, false discovery rate correction across the nine analyzed elements, and Holm adjustment for pairwise comparisons. Finally, the robustness of the principal Mg finding was evaluated through sensitivity analyses addressing both an atypical multielement profile and the contribution of bilateral specimens from one patient.

Taken together, our findings support the concept that elemental composition within the osteonecrotic femoral head is spatially heterogeneous and element-specific. The most consistent observation was the relative depletion of Mg in necrotic bone, a pattern that remained robust after multiple-testing correction and sensitivity analyses and that is consistent with earlier observations of reduced Mg concentrations in osteonecrotic femoral heads [4]. This finding, together with evidence that bone elemental composition varies according to anatomical compartment and local pathological remodeling [7–9], suggests that the elemental profile of necrotic tissue may reflect disturbances in local mineral homeostasis associated with ischemic injury, resorption, and repair. In contrast, the higher Pb concentration observed in necrotic than in compact bone represents a weaker and exploratory signal that requires confirmation, while the absence of a compartmental gradient for Co suggests that some elements associated with ONFH at the whole-bone level may be distributed more diffusely throughout the femoral head [2]. These results highlight the importance of considering the precise anatomical compartment from which bone specimens are obtained when interpreting elemental concentrations in ONFH and provide a rationale for future studies integrating elemental analysis with histological, vascular, and bone-remodeling assessments.

Conclusion

Elemental composition varied across bone compartments in osteonecrotic femoral heads. Magnesium showed the clearest difference, with lower concentrations in necrotic bone than in cancellous and compact bone, suggesting altered local mineral homeostasis. Lead showed only an exploratory trend toward higher concentrations in necrotic bone. These findings highlight the importance of sampling location in elemental studies of ONFH. Further research is needed to determine whether these changes contribute to osteonecrosis or result from necrosis and bone remodeling.

Abbreviations

As

Arsenic

Cd

Cadmium

CEM

Comité d'Éthique Médicale (Medical Ethics Committee)

Co

Cobalt

Cr

Chromium

CRDL

Lubumbashi Sickle Cell Disease Reference Center (*Centre de Référence de la Drépanocytose de Lubumbashi*)

Cu

Copper

CV_i

Coefficient of variation for intermediate precision

CV_r

Coefficient of variation for repeatability

D

Cortical (dense) bone compartment

DRC

Democratic Republic of the Congo

FDR

False discovery rate

HCl

Hydrochloric acid

HNO₃

Nitric acid

ICP-OES

Inductively coupled plasma optical emission spectrometry

IQR

Interquartile range

IRSS

Institute for Health Sciences Research (*Institut de Recherche en Sciences de la Santé*)

LOD

Limit of detection

LOQ

Limit of quantification

Mg

Magnesium

N

Necrotic bone compartment

Ni

Nickel

OCC

Office Congolais de Contrôle

ONFH

Osteonecrosis of the femoral head

Pb

Lead

S

Cancellous bone compartment

SD

Standard deviation

UNILU

University of Lubumbashi

USA

United States of America

Zn

Zinc

Declarations

Conflict of Interest

The authors declare that they have no conflicts of interest.

Ethics Approval and Consent to Participate

The study was approved by the Medical Ethics Committee of the University of Lubumbashi (reference: UNILU/CEM/131/2022) and was conducted in accordance with the Declaration of Helsinki. Written

informed consent was obtained from all participants before inclusion. Bone specimens were obtained from tissue removed during routine therapeutic total hip arthroplasty, with no additional invasive procedure performed for research purposes.

Funding

The authors received no specific funding for this research, authorship, or publication.

Author Contribution

Cedrick Sangwa Milindi conceived and designed the study, coordinated data and sample collection, performed the statistical analysis, interpreted the results, and drafted the manuscript. Célestin Banza Lubaba contributed to the toxicological interpretation, analytical methodology, and critical revision of the manuscript. Mireille Kakinga Zabibu contributed to sample processing, data interpretation, and manuscript revision. Adelin Muganza contributed to the study design, scientific supervision, and critical revision of the manuscript. Arthur Kaniki contributed to the analytical methodology, interpretation of elemental measurements, and critical review of the manuscript. Willy Arung A Kalau contributed to scientific supervision, interpretation of the findings, and manuscript revision. Luc Mokassa provided overall academic supervision, contributed to the study design and interpretation of the results, and critically revised the manuscript. All authors read and approved the final version of the manuscript.

Acknowledgement

The authors thank the staff of the OCC in Lubumbashi for their technical assistance with elemental analyses, particularly Engineer Kitwa, whose expertise made a valuable contribution to this work.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Tables

Table 1 is not available with this version.

Figures



Figure 1

Anteroposterior pelvic radiograph of a 48-year-old patient showing a right total hip arthroplasty and advanced left hip osteoarthritis secondary to end-stage osteonecrosis of the femoral head.

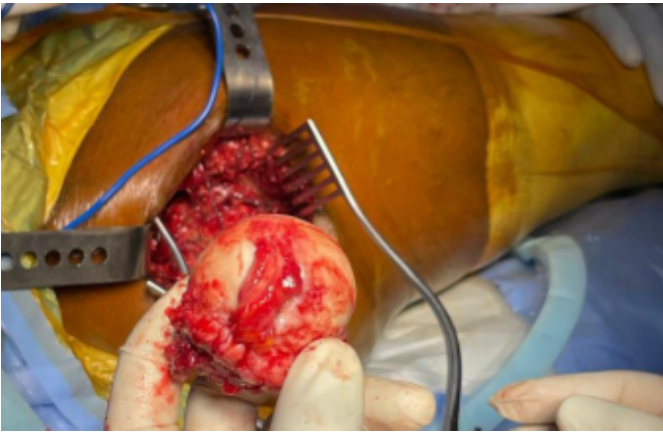


Figure 2

Intraoperative appearance of an osteonecrotic femoral head during total hip arthroplasty.

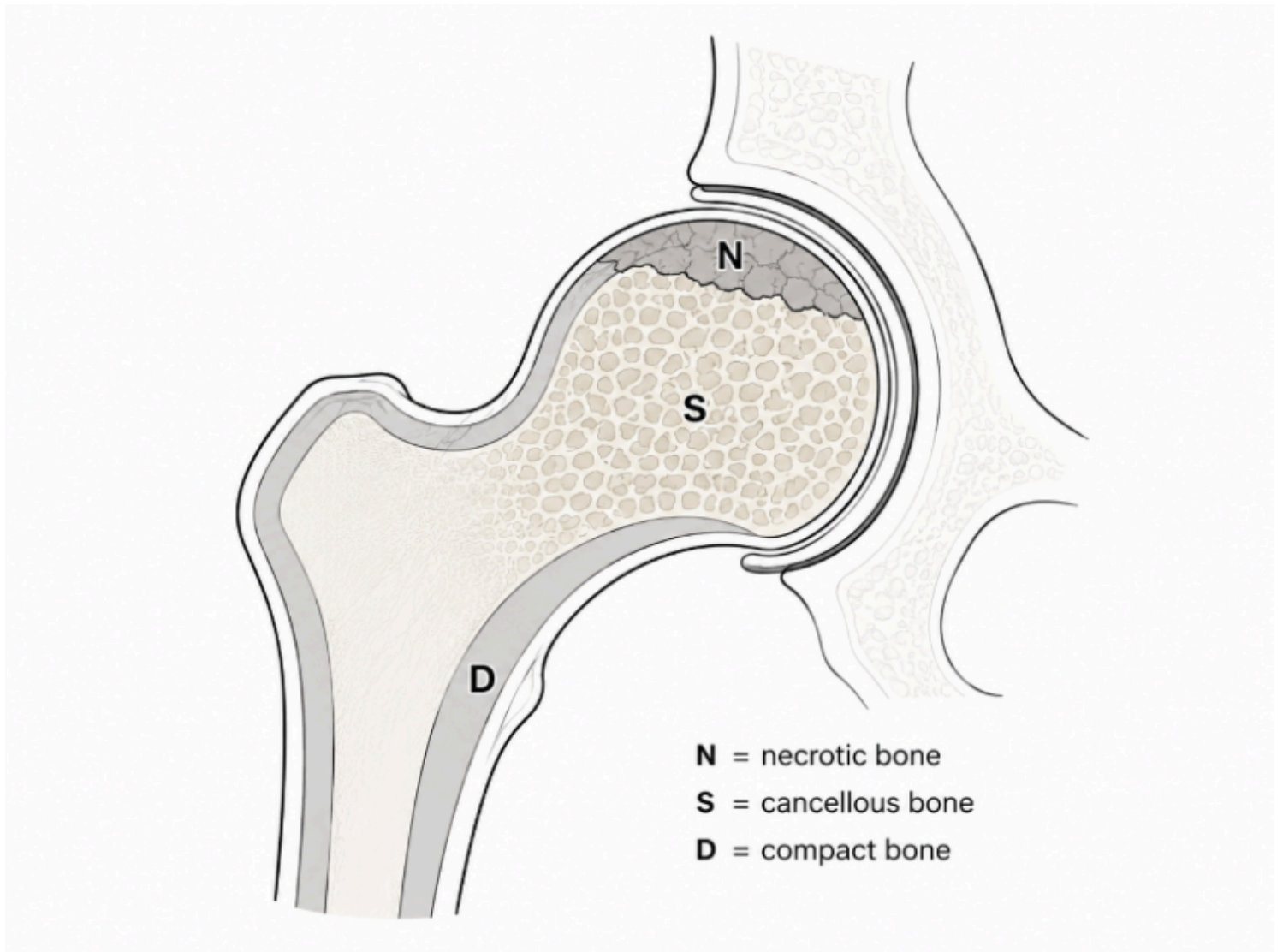


Figure 3

Schematic illustration of the three paired sampling compartments of the femoral head: necrotic bone (N), cancellous bone (S), and compact bone (D).

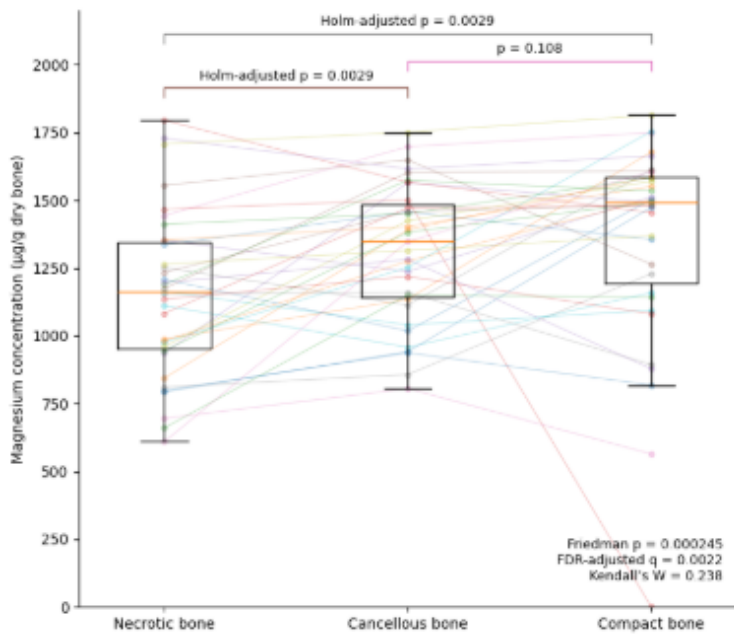


Figure 4

Paired distribution of magnesium concentrations across bone compartments in osteonecrotic femoral heads. Individual lines connect magnesium concentrations measured in necrotic, cancellous, and compact bone from the same femoral head. Boxplots represent the median and interquartile range.

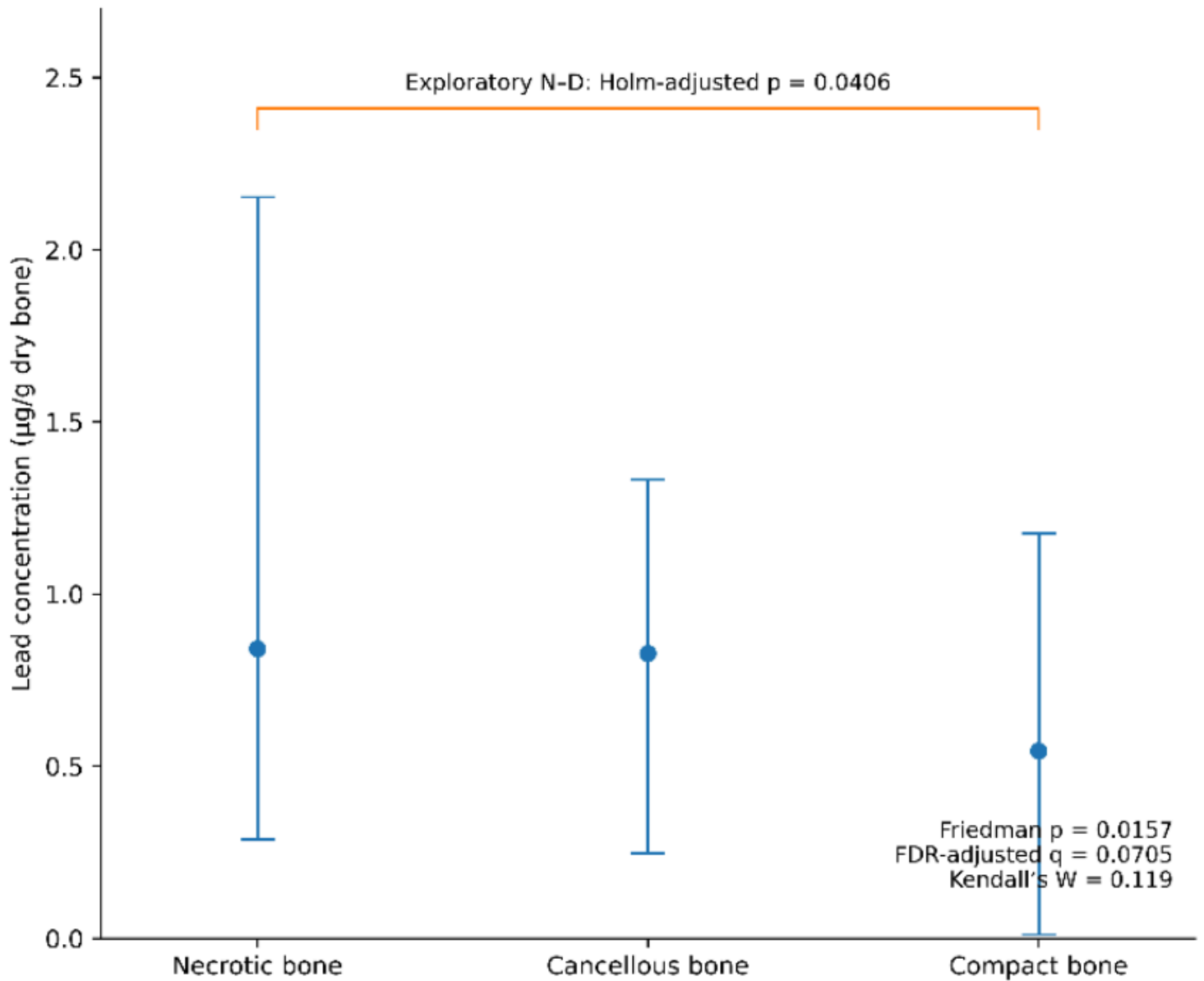


Figure 5

Compartment-specific distribution of lead concentrations in osteonecrotic femoral heads. Points represent median Pb concentrations and error bars represent interquartile ranges for necrotic, cancellous, and compact bone.