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Research Article

The Correlation between Bone Mineral Density and Particulate Matter in Patients with Osteoporosis

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Abstract

Background: This study examined the correlation between bone mineral density (BMD) and particulate matter (PM) in patients with osteoporosis.
Methods: People with osteopenia, osteoporosis, and normal BMD were included in the study. BMD, bone mineral content (BMC), T-scores, and Z-scores of the lumbar vertebrae (L1-L4) and femur were obtained by dual-energy X-ray absorptiometry (DEXA). Daily $PM_{2.5}$ and PM_{10} concentrations during the study period (January 21, 2022, to May 21, 2023) were obtained from local monitoring stations, with missing data estimated using satellite-derived aerosol optical depth (AOD).
Results: In patients with osteoporosis, inverse correlations were observed between $PM_{2.5}$ and PM_{10} and BMD, BMC, T-scores, and Z-scores in different parts of the femur (except femoral neck T-score) and lumbar spine. Still, none of the correlations was statistically significant.
Conclusion: There was no significant correlation between the mean concentration of $PM_{2.5}$ and PM_{10} and the parameters of BMD, BMC, T-score, and Z-score in the bones of the femur and lumbar spine of patients with osteoporosis.

Keywords: Osteoporosis; Femur; Particulate Matter

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Background

Air pollution is a significant threat to global health, leading to adverse health outcomes and increased mortality (1). Evidence of a positive relationship between short-term exposure to pollutants and cardiovascular, respiratory, and cerebrovascular mortality has been found (2).

Osteoporosis is a disease characterized by structural deterioration of bone tissue, decreased bone mass, and increased bone fragility, and annually leads to nearly nine million fractures worldwide (3). The number of bone fractures due to osteoporosis is predicted to increase 2.28 times over the next few decades in Asia, leading to increased health care costs (4). The severity of osteoporosis is linked to inflammation caused by air pollutants, especially particulate matter (PM) (5). The evidence suggests an increase in osteoporosis and the risk of fractures associated with osteoporosis due to exposure to outdoor air pollutants; however, given the limited number of studies and the observed heterogeneity, these results should be interpreted with caution (6).

Osteoporosis has a significant relationship with PM_{10}, but this relationship with $PM_{2.5}$ is still unclear; however, the negative effects of pollutants on bone mineral density (BMD) are evident. PM leads to osteoporosis and bone fractures indirectly, for example, through reduced ultraviolet (UV)-B radiation and vitamin D absorption (7). Other studies have shown that long-term exposure to PM is associated with a decrease in BMD T-scores and an increased risk of osteoporosis. Additionally, the side effects of nitrogen dioxide (NO_2), PM_{10}, and $PM_{2.5}$ were more pronounced in men than in women (8-11). Exposure to air pollution can increase the risk of osteoporosis by interacting with genetic factors (12). Reducing levels of NO_2, $PM_{2.5}$, and PM_{10} in the air may lower the risk of hip fractures and related short-term mortality among elderly individuals (13). Exposure to air pollution is linked to an increased risk of hip fractures (14).

Increased levels of air pollutants were linked to bone damage, particularly in the lumbar spine, among postmenopausal women (15). Poor air quality is a controllable risk factor for osteoporosis and bone fractures (16).

Abadan is a city located in Khuzestan Province, southwestern Iran. It is known for being one of the hottest places on Earth and frequently experiences dust storms due to its proximity to large deserts in southern Iraq and Saudi Arabia (17). This research is crucial due to the frequent air pollution in this region and the scarcity of studies examining the relationship between PM and BMD in individuals with osteoporosis. Additionally, global studies on patients with osteoporosis are also limited and have produced inconsistent results, highlighting the need for more research in this area.

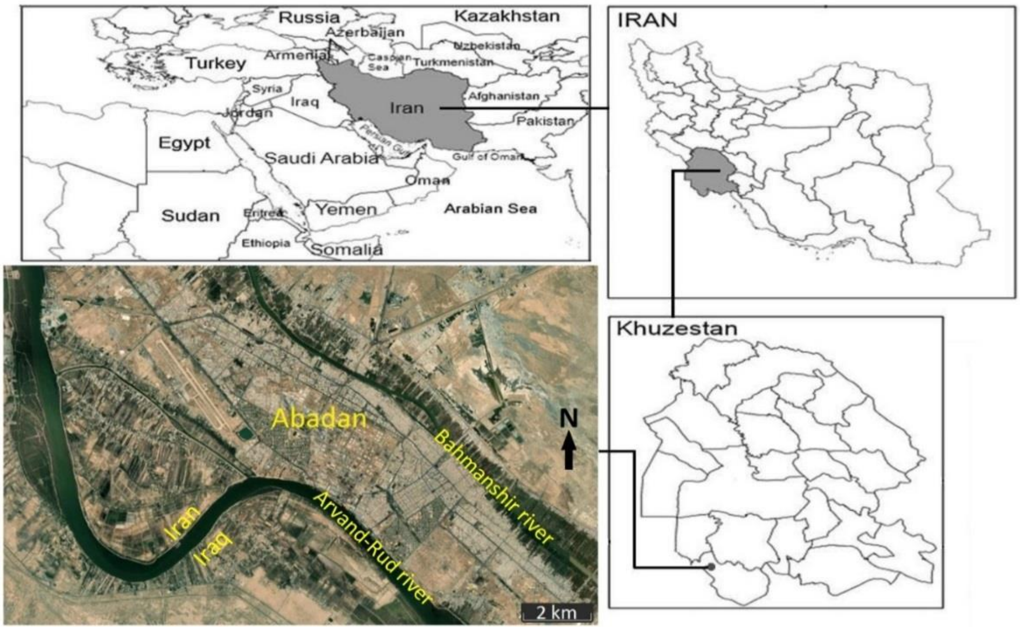

Figure 1. Geographical location of Abadan City in Khuzestan Province, Iran, and in the Middle East

Methods

Study Area: Abadan, located in southwest Iran (Figure 1), is exposed to industrial pollutants and annual dust storms due to its industrial nature and proximity to countries with active sources of dust (17).

Participants: This cross-sectional study included individuals referred to the Bone Density Measurement Department at Abadan Nuclear Medicine Center from January 21, 2022, to May 21, 2023.

Demographic information and BMD, bone mineral content (BMC), T-scores, and Z-scores related to the patients' left femur (neck, greater trochanter, intertrochanteric, total hip, and Ward's triangle) and lumbar spine (L1-L4) were received. Based on the T-scores, the patients were categorized as follows: T-scores higher than -1 were considered healthy in terms of BMD. Those with a T-score between -1 and -2.5 were classified as having osteopenia (low bone density). Individuals with a T-score less than -2.5 were classified as having osteoporosis (18). The exclusion criteria comprised incomplete BMD records.

BMD Measurement: BMD was assessed using dual-energy X-ray absorptiometry (DEXA), the standard method for evaluating bone density. This method uses X-rays to measure bone density, which determines the hardness and firmness of bones in the body.

PM Concentration Measurement: Similar to the information period of Abadan Nuclear Medicine Center (January 21, 2022, to May 21, 2023), air PMs (PM_{10} and $PM_{2.5}$) were collected from the Abadan Environmental Protection Department. The PM concentration levels were used to determine the air quality index (AQI). The Met One Beta Attenuation Monitor was used to observe particle mass concentration (19, 20). Meteorological data, including air temperature, relative humidity, dew point, wind speed and direction, and air pressure, were retrieved from the Iran Meteorological Organization's website (www.irimo.ir). Since there were several days with no PM data during the study period, aerosol optical depth (AOD) was used to estimate PM_{10} and $PM_{2.5}$, as shown in figure 2. AOD data were collected with a daily temporal resolution and 1° spatial resolution from the Giovanni NASA website (https://giovanni.gsfc.nasa.gov/giovanni). The satellite-based datasets on AOD are commonly utilized in numerous studies to estimate the concentration of PMs ($PM_{2.5}$ and PM_{10}) in the tropospheric region (21, 22). AOD measures the amount of light extinction in the atmosphere due to aerosol scattering and absorption. These particles affect the earth's energy balance by scattering and absorbing radiation and alter cloud properties (23).

Statistical Analysis Method: Data were recorded in Excel software, which were later transferred to SPSS software (version 16, SPSS Inc., Chicago, IL, USA) for data analysis. Mean ± standard deviation (SD) and frequency distribution were used to summarize the data. The Shapiro-Wilk test was performed to assess the normality of continuous variables. Analysis of variance (ANOVA) was used to analyze differences between multiple groups, followed by the Tukey post-hoc test for pairwise comparisons. The chi-square test was applied to examine the association between categorical variables. Bivariate correlation analysis, specifically Pearson's correlation coefficient, was performed to assess the relationship between two continuous variables. All statistical analyses in this study were performed using SPSS software. A significance level of 0.05 was adopted for all tests to determine statistical significance.

Results

Between January 21, 2022, and May 21, 2023, 295 individuals, primarily women (89.20%), with a mean age of 57.73 ± 10.91 years, were referred to the bone densitometry department at Abadan Nuclear Medicine Center. Of these, 231 (78.3%) were 50 years old or older.

Bone density was measured in the left femur (neck, greater trochanter, intertrochanteric, total hip, and Ward's triangle) and the lumbar spine (L1-L4). Participants were grouped as normal, osteopenia, or osteoporosis based on their T-score.

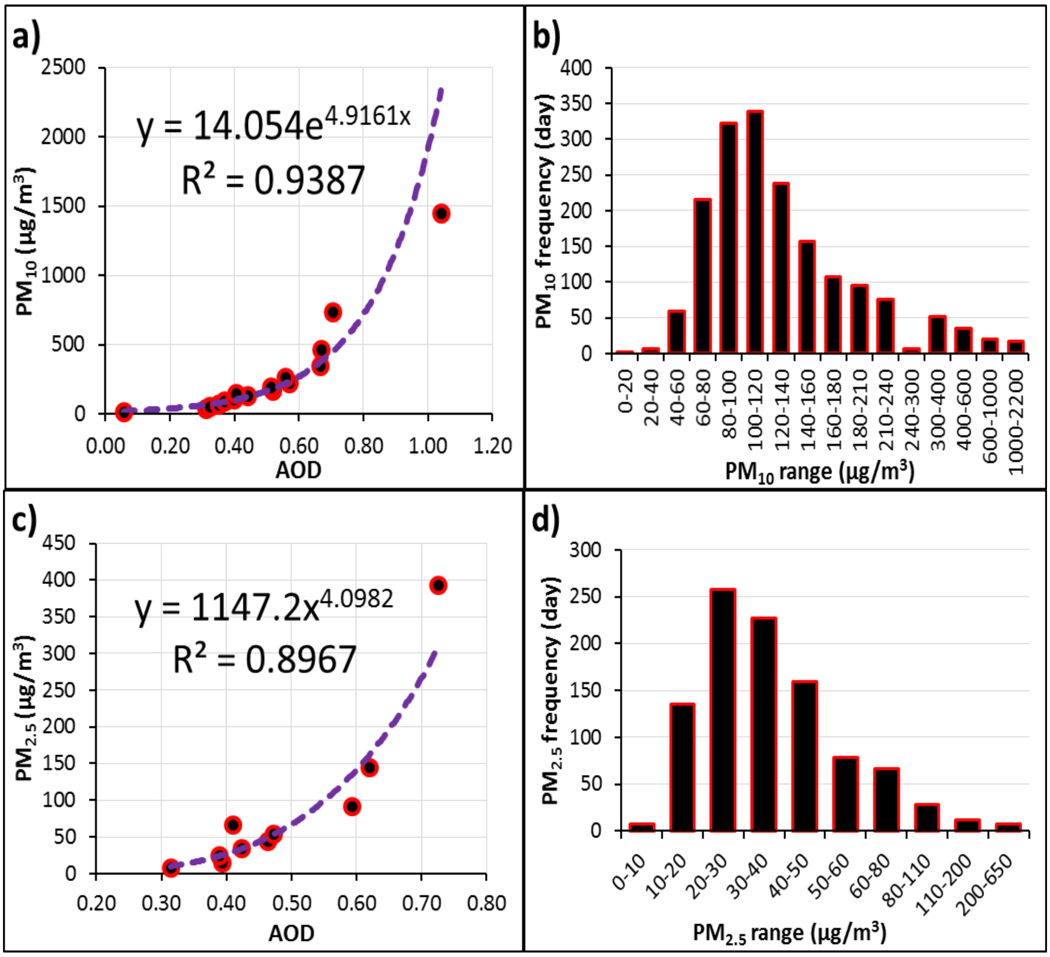

Figure 2. a) Particulate matter (PM)10 and c) PM2.5 formulation with aerosol optical depth (AOD) and their associated (b and d) histograms in Abadan City, Iran, during March 2011 and April 2023

Comparison of Age and Sex Distribution among Femurs in Groups: 126 individuals had normal femur T-scores, 139 had osteopenia, and 30 had osteoporosis. Most participants were women over 50 years across all groups. In the osteoporosis group, all patients were over 50 years old, with a mean age of 67.40 ± 8.50 years, which was significantly higher than the mean ages in the osteopenia (58.01 ± 10.26 years) and normal (55.12 ± 10.84 years) groups ($P < 0.001$). The gender distribution showed a higher proportion of women in all groups (85.7% normal, 92.1% osteopenia, and 90.0% osteoporosis), but the differences were not statistically significant ($P = 0.247$) (Table 1).

Comparison of Bone Health Parameters in the Femur: Significant differences were observed in mean BMD across the three groups ($P < 0.001$), with the lowest value in osteoporosis (0.57 ± 0.06 g/cm²) and the highest in the normal group (0.94 ± 0.09 g/cm²). Similarly, mean BMC was significantly lower in osteoporosis (2.46 ± 0.70 g) compared to osteopenia (3.06 ± 0.66 g) and normal (3.79 ± 0.84 g) groups ($P < 0.001$).

These patterns held for BMD and BMC in different femoral regions (neck, greater trochanter, intertrochanteric, total hip, and Ward's triangle), where the osteoporosis group consistently showed the lowest values (all Ps < 0.001). No significant differences were found in area measurements across groups (Table 2).

Comparison of Age and Sex Distribution among Lumbar Spine in Groups: For the lumbar spine (L1-L4), participants were classified as normal BMD (n = 130), osteopenia (n = 100), or osteoporosis (n = 65) based on T-scores. The mean age in the osteoporosis group was 60.92 ± 9.64 years, significantly higher than that in the normal BMD group (56.35 ± 10.63 years) and the osteopenia group (57.45 ± 11.69 years) ($P = 0.021$).

Table 1. Comparison of age and gender distribution in the groups

Variable			Normal	Osteopenia	Osteoporosis	Total (n = 295)	P-value
Femur	Age (year)	Mean ± SD	55.12 ± 10.84	58.01 ± 10.26	67.40 ± 8.50	57.73 ± 10.91	< 0.001*
		50	38 (30.2)	26 (18.7)	0 (0)	64 (21.7)	< 0.001†
		> 50	88 (69.8)	113 (81.3)	30 (100)	231 (78.3)	
	Sex n (%)	Female	108 (85.7)	128 (92.1)	27 (90.0)	263 (89.2)	0.247†
		Male	18 (14.3)	11 (7.9)	3 (10.0)	32 (10.8)	
Lumbar spine	Age (year)	Mean ± SD	56.35 ± 10.63	57.45 ± 11.69	60.92 ± 9.64	57.73 ± 10.91	0.021*
		50	35 (26.9)	22 (22.0)	7 (10.8)	64 (21.7)	0.036†
		> 50	95 (73.1)	78 (78.0)	58 (89.2)	231 (78.3)	
	Sex n (%)	Female	109 (83.8)	92 (92.0)	62 (95.4)	263 (89.2)	0.027†
		Male	21 (16.2)	8 (8.0)	3 (4.6)	32 (10.8)	

SD: Standard deviation
*P-value conducted from One-way ANOVA. †P-value conducted from Chi-square test.

Table 2. Comparison of bone health parameters in femur

Variable	Femur				P-value*
	Normal (n = 126) (mean ± SD)	Osteopenia (n = 139) (mean ± SD)	Osteoporosis (n = 30) (mean ± SD)	Total (n = 295) (mean ± SD)	
BMD (g/cm²)	0.94 ± 0.09	0.75 ± 0.05	0.57 ± 0.06	0.81 ± 0.14	< 0.001
BMC (g)	3.79 ± 0.84	3.06 ± 0.66	2.46 ± 0.70	3.31 ± 0.87	< 0.001
Area (cm²)	4.01 ± 0.78	4.13 ± 0.78	4.32 ± 1.10	4.10 ± 0.82	0.149
Neck T-score	0.02 ± 0.72	-1.56 ± 0.39	-2.87 ± 0.65	-1.02 ± 1.13	< 0.001
Neck T- percent	0.17 ± 9.51	-20.56 ± 5.34	-39.50 ± 6.48	-13.63 ± 15.12	< 0.001
Neck Z- score	1.03 ± 0.91	-0.39 ± 0.56	-1.40 ± 0.57	0.11 ± 1.12	< 0.001
Neck Z- percent	15.95 ± 15.38	-5.67 ± 8.60	-23.23 ± 8.80	1.78 ± 17.86	< 0.001
GT BMD (g/cm²)	0.76 ± 0.11	0.63 ± 0.08	0.48 ± 0.11	0.67 ± 0.13	< 0.001
GT BMC (g)	7.05 ± 1.72	5.80 ± 1.33	4.47 ± 1.69	6.20 ± 1.75	< 0.001
GT Area (cm²)	9.21 ± 2.13	9.31 ± 1.56	9.08 ± 2.41	9.24 ± 1.91	0.794
GT T- score	-0.19 ± 0.91	-1.35 ± 0.68	-2.62 ± 0.97	-0.99 ± 1.12	< 0.001
GT T- percent	-3.25 ± 13.05	-19.26 ± 10.44	-37.87 ± 13.82	-14.32 ± 16.22	< 0.001
GT Z- score	0.48 ± 0.98	-0.60 ± 0.80	-2.21 ± 4.23	-0.30 ± 1.77	< 0.001
GT Z- percent	7.76 ± 15.98	-8.96 ± 11.98	-25.73 ± 16.53	-3.53 ± 17.94	< 0.001
Inter BMD (g/cm²)	1.22 ± 0.14	1.04 ± 0.12	0.80 ± 0.14	1.09 ± 0.18	< 0.001
Inter BMC (g)	24.58 ± 3.88	20.76 ± 2.80	16.47 ± 3.65	21.96 ± 4.25	< 0.001
Inter Area (cm²)	20.20 ± 2.23	19.97 ± 1.64	20.43 ± 2.23	20.12 ± 1.97	0.428
Inter T- score	-0.02 ± 0.80	-1.04 ± 0.62	-2.39 ± 0.79	-0.74 ± 1.03	< 0.001
Inter T- percent	-0.37 ± 11.42	-14.52 ± 8.97	-33.93 ± 10.97	-10.45 ± 14.59	< 0.001
Inter Z- score	0.52 ± 0.89	-0.37 ± 0.72	-1.34 ± 0.82	-0.09 ± 1.00	< 0.001
Inter Z- percent	8.50 ± 14.36	-5.39 ± 11.06	-22.13 ± 12.98	-1.16 ± 15.97	< 0.001
Total Hip BMD (g/cm²)	1.06 ± 0.11	0.89 ± 0.09	0.69 ± 0.11	0.94 ± 0.15	< 0.001
Total Hip BMC (g)	35.42 ± 5.75	29.69 ± 3.92	23.41 ± 5.46	31.50 ± 6.25	< 0.001
Total Hip Area (cm²)	33.43 ± 3.71	33.41 ± 3.02	33.82 ± 4.32	33.46 ± 3.46	0.835
Total Hip T- score	0.01 ± 0.74	-1.09 ± 0.55	-2.44 ± 0.74	-0.76 ± 1.01	< 0.001
Total Hip T- percent	-0.13 ± 10.97	-15.65 ± 7.85	-34.90 ± 10.47	-10.98 ± 14.49	< 0.001
Total Hip Z- score	0.56 ± 0.86	-0.47 ± 0.86	-1.38 ± 0.79	-0.12 ± 1.07	< 0.001
Total Hip Z- percent	9.21 ± 13.82	-6.19 ± 10.06	-22.93 ± 12.48	-1.32 ± 15.82	< 0.001
Ward Triangle BMD (g/cm²)	0.76 ± 0.12	0.63 ± 0.57	0.46 ± 0.18	0.67 ± 0.42	< 0.001
Ward Triangle BMC (g)	0.76 ± 0.12	0.57 ± 0.12	2.07 ± 8.87	0.81 ± 2.83	0.030
Ward Triangle Area (cm²)	1.75 ± 8.64	1.67 ± 8.14	0.96 ± 0.16	1.64 ± 7.93	0.884

SD: Standard deviation
*P-value conducted from One-way ANOVA
BMD: Bone mineral density; BMC: Bone mineral content; GT: Greater trochanter; Inter: Intertrochanteric

Age distribution showed fewer individuals ≤50 years in osteoporosis (10.8%) compared to osteopenia (22.0%) and normal (26.9%) groups (P = 0.036). The proportion of women was the highest in osteoporosis (95.4%), followed by osteopenia (92.0%) and normal (83.8%), with a significant difference (P = 0.027) (Table 1).

Comparison of Bone Health Parameters in Lumbar Spine: Total BMD differed significantly among groups (P < 0.001), with the lowest mean in osteoporosis (0.69 ± 0.08 g/cm²) and the highest in normal (1.13 ± 0.21 g/cm²) group. Total BMC was also the lowest in osteoporosis (39.48 ± 8.01 g) compared to osteopenia (48.45 ± 6.89 g) and normal (67.12 ± 19.01 g) groups (P < 0.001). These differences extended to individual vertebrae (L1-L4), where BMD, BMC, T-scores, and Z-scores were significantly lower in osteoporosis (all Ps < 0.001). Area measurements showed minor differences (e.g., total area: P = 0.033), but trends were consistent (Table 3).

Table 3. Comparison of bone health parameters in lumbar spine

Variable	Lumbar Spine				P-value*
	Normal (n = 130) (mean ± SD)	Osteopenia (n = 100) (mean ± SD)	Osteoporosis (n = 65) (mean ± SD)	Total (n = 295) (mean ± SD)	
L1 BMD (g/cm²)	0.97 ± 0.17	0.79 ± 0.08	0.62 ± 0.09	0.83 ± 0.19	< 0.001
L1 BMC (g)	12.89 ± 3.31	9.84 ± 1.73	7.99 ± 1.91	10.78 ± 3.26	< 0.001
L1 Area (cm²)	13.07 ± 2.07	12.64 ± 1.41	12.79 ± 1.75	12.86 ± 1.80	0.202
L1 T-score	-0.12 ± 1.30	-1.83 ± 0.66	-3.31 ± 0.80	-1.41 ± 1.62	< 0.001
L1 T-percent	-1.50 ± 14.69	-20.97 ± 7.46	-36.38 ± 13.01	-15.84 ± 18.53	< 0.001
L1 Z-score	0.81 ± 1.37	-1.02 ± 1.83	-2.34 ± 2.18	-0.51 ± 2.14	< 0.001
L1 Z-percent	10.67 ± 18.54	-9.96 ± 10.06	-27.17 ± 11.13	-4.64 ± 20.89	< 0.001
L2 BMD (g/cm²)	1.08 ± 0.21	0.85 ± 0.06	0.65 ± 0.20	0.91 ± 0.24	< 0.001
L2 BMC (g)	15.25 ± 4.88	11.53 ± 1.62	9.13 ± 2.07	12.64 ± 4.29	< 0.001
L2 Area (cm²)	13.89 ± 2.32	13.44 ± 2.01	13.43 ± 1.84	13.63 ± 2.12	0.192
L2 T-score	0.08 ± 1.71	-2.00 ± 0.56	-3.44 ± 1.25	-1.41 ± 1.93	< 0.001
L2 T-percent	0.14 ± 15.70	-20.96 ± 5.90	-37.14 ± 8.57	-15.28 ± 18.90	< 0.001
L2 Z-score	1.10 ± 1.83	-0.85 ± 0.70	-2.23 ± 0.95	-0.30 ± 1.90	< 0.001
L2 Z-percent	13.43 ± 22.75	-10.05 ± 8.18	-26.84 ± 10.90	-3.38 ± 23.15	< 0.001
L3 BMD (g/cm²)	1.18 ± 0.25	0.89 ± 0.10	0.72 ± 0.10	0.98 ± 0.26	< 0.001
L3 BMC (g)	17.94 ± 6.48	12.75 ± 2.07	10.45 ± 2.57	14.53 ± 5.59	< 0.001
L3 Area (cm²)	15.09 ± 2.67	14.23 ± 2.07	14.53 ± 1.94	14.68 ± 2.35	0.018
L3 T-score	0.76 ± 1.75	-1.61 ± 0.63	-3.12 ± 0.93	-0.90 ± 2.04	< 0.001
L3 T-percent	8.12 ± 18.38	-17.03 ± 6.60	-32.54 ± 9.47	-9.43 ± 21.34	< 0.001
L3 Z-score	2.00 ± 3.34	-0.47 ± 0.81	-1.70 ± 1.18	0.35 ± 2.79	< 0.001
L3 Z-percent	21.73 ± 23.55	-4.60 ± 10.30	-20.75 ± 13.30	3.46 ± 24.81	< 0.001
L4 BMD (g/cm²)	1.21 ± 0.27	0.91 ± 0.17	0.74 ± 0.10	1.00 ± 0.29	< 0.001
L4 BMC (g)	21.28 ± 8.63	14.53 ± 2.38	11.78 ± 2.55	16.90 ± 7.22	< 0.001
L4 Area (cm²)	17.21 ± 3.46	15.86 ± 2.42	15.81 ± 2.65	16.44 ± 3.03	< 0.001
L4 T-score	1.32 ± 2.42	-1.23 ± 0.75	-2.88 ± 0.91	-0.47 ± 2.42	< 0.001
L4 T-percent	14.19 ± 25.89	-13.23 ± 7.93	-30.48 ± 9.61	-4.92 ± 25.82	< 0.001
L4 Z-score	2.34 ± 2.54	-0.12 ± 1.06	-1.58 ± 0.98	0.65 ± 2.45	< 0.001
L4 Z-percent	29.06 ± 31.88	-1.00 ± 13.44	-19.27 ± 11.95	8.35 ± 30.46	< 0.001
Total BMD (g/cm²)	1.13 ± 0.21	0.86 ± 0.05	0.69 ± 0.80	0.95 ± 0.23	< 0.001
Total BMC (g)	67.12 ± 19.01	48.45 ± 6.89	39.48 ± 8.01	54.70 ± 17.93	< 0.001
Total Area (cm²)	58.92 ± 9.50	56.32 ± 6.29	56.70 ± 7.03	57.55 ± 8.07	0.033
Total T-score	0.66 ± 1.80	-1.64 ± 0.40	-3.20 ± 0.76	-0.97 ± 2.00	< 0.001
Total T-percent	7.05 ± 19.10	-17.74 ± 4.48	-34.26 ± 7.81	-10.45 ± 21.43	< 0.001
Total Z-score	1.65 ± 1.93	-0.53 ± 0.70	-1.91 ± 0.85	0.14 ± 2.01	< 0.001
Total Z-percent	20.65 ± 24.37	-5.75 ± 8.93	-23.41 ± 10.00	2.08 ± 25.01	< 0.001

SD: Standard deviation
*P-value conducted from One-way ANOVA
BMD: Bone mineral density; BMC: Bone mineral content

Table 4. Comparison of the mean concentration of particulate matters (PM) and aerosol optical depth (AOD) with the frequency of the number of people in the groups

Variable		Groups				P-value*
		Normal (n = 130) (mean ± SD)	Osteopenia (n = 100) (mean ± SD)	Osteoporosis (n = 65) (mean ± SD)	Total (n = 295) (mean ± SD)	
PM2.5 (μg/m^3)	Lumbar spine	84.68 ± 115.44	108.09 ± 153.21	66.68 ± 63.80	88.65 ± 121.99	0.091
PM10 (μg/m^3)		169.49 ± 162.59	197.44 ± 213.15	150.45 ± 94.57	174.77 ± 170.77	0.202
AOD		0.41 ± 0.15	0.44 ± 0.16	0.41 ± 0.13	0.42 ± 0.15	0.212
PM2.5 (μg/m^3)	Femur	89.05 ± 105.40	93.68 ± 145.58	63.67 ± 36.79	88.65 ± 121.99	0.475
PM10 (μg/m^3)		171.74 ± 137.28	183.14 ± 210.29	148.73 ± 148.73	174.77 ± 170.77	0.587
AOD		0.43 ± 0.14	0.42 ± 0.16	0.42 ± 0.42	0.42 ± 0.15	0.840

*P-value conducted from One-way ANOVA
SD: Standard deviation
AOD: Aerosol optical depth; PM: Particulate matters

Comparison of the Mean Concentration of PM and AOD with the Frequency of the Number of People in the Groups in which the Femur and Lumbar Spine Was Examined: The mean concentrations of $PM_{2.5}$, PM_{10}, and AOD on the days of patient admission to the bone densitometry department at Abadan Nuclear Medicine Center were 88.65 ± 121.99, 174.77 ± 170.77, and 0.42 ± 0.15 μg/m^3, respectively.

For both femur and lumbar spine classifications, there was no significant difference in the mean concentration of $PM_{2.5}$, PM_{10}, and AOD on reference days for all three groups (normal, osteopenia, and osteoporosis) (Table 4).

The Correlation between PM and AOD with Femur Bone Parameters in Patients with Osteoporosis: Table 5 displays the correlation between PM and AOD with femur bone parameters in patients with osteoporosis.

Table 5. The correlation between particulate matters (PM) and aerosol optical depth (AOD) with femur bone parameters in patients with osteoporosis

		SMEAN [$PM_{2.5}$(μg/m^3)]	SMEAN [PM_{10}(μg/m^3)]	SMEAN (AOD)
BMD (g/cm^2)	Pearson Correlation	-0.106	-0.115	-0.168
	Sig. (2-tailed)	0.576	0.544	0.375
BMC (g)	Pearson Correlation	-0.060	-0.069	-0.162
	Sig. (2-tailed)	0.752	0.717	0.393
Area (cm^2)	Pearson Correlation	-0.004	-0.014	-0.110
	Sig. (2-tailed)	0.984	0.941	0.564
Neck T-score	Pearson Correlation	0.060	0.017	-0.123
	Sig. (2-tailed)	0.754	0.928	0.518
Neck T-percent	Pearson Correlation	-0.086	-0.089	-0.142
	Sig. (2-tailed)	0.651	0.640	0.455
Neck Z-score	Pearson Correlation	-0.075	-0.043	-0.005
	Sig. (2-tailed)	0.695	0.823	0.977
Neck Z-percent	Pearson Correlation	-0.057	-0.025	-0.011
	Sig. (2-tailed)	0.765	0.896	0.955
GT BMD (g/ cm^2)	Pearson Correlation	-0.196	-0.234	-0.309
	Sig. (2-tailed)	0.299	0.213	0.096
GT BMC (g)	Pearson Correlation	-0.242	-0.224	-0.189
	Sig. (2-tailed)	0.198	0.235	0.317
GT Area (cm^2)	Pearson Correlation	-0.193	-0.129	-0.006
	Sig. (2-tailed)	0.306	0.497	0.974
GT T-score	Pearson Correlation	-0.195	-0.233	-0.313
	Sig. (2-tailed)	0.303	0.215	0.093
GT_T-percent	Pearson Correlation	-0.189	-0.227	-0.307
	Sig. (2-tailed)	0.317	0.228	0.099
GT_Z-score	Pearson Correlation	-0.158	-0.127	-0.051
	Sig. (2-tailed)	0.405	0.503	0.790
GT_Z-percent	Pearson Correlation	-0.175	-0.196	-0.250
	Sig. (2-tailed)	0.354	0.299	0.182
Inter BMD (g/ cm^2)	Pearson Correlation	-0.279	-0.209	-0.197
	Sig. (2-tailed)	0.135	0.267	0.296
Inter BMC (g)	Pearson Correlation	-0.189	-0.143	-0.159
	Sig. (2-tailed)	0.317	0.452	0.400
Inter Area (cm^2)	Pearson Correlation	0.083	0.074	0.023
	Sig. (2-tailed)	0.662	0.697	0.902
Inter T-score	Pearson Correlation	-0.283	-0.207	-0.193
	Sig. (2-tailed)	0.129	0.272	0.308
Inter T-percent	Pearson Correlation	-0.282	-0.210	-0.197
	Sig. (2-tailed)	0.131	0.266	0.298
Inter Z-score	Pearson Correlation	-0.237	-0.135	-0.063
	Sig. (2-tailed)	0.208	0.478	0.741
Inter Z-percent	Pearson Correlation	-0.235	-0.137	-0.085
	Sig. (2-tailed)	0.212	0.471	0.656
Total Hip BMD (g/ cm^2)	Pearson Correlation	-0.208	-0.185	-0.231
	Sig. (2-tailed)	0.269	0.326	0.220
Total Hip BMC (g)	Pearson Correlation	-0.209	-0.173	-0.186
	Sig. (2-tailed)	0.268	0.360	0.326
Total Hip Area (cm^2)	Pearson Correlation	-0.065	-0.037	-0.019
	Sig0. (2-tailed)	0.731	0.847	0.920
Total Hip T-score	Pearson Correlation	-0.248	-0.203	-0.220
	Sig. (2-tailed)	0.187	0.281	0.242
Total Hip T percent	Pearson Correlation	-0.243	-0.200	-0.220
	Sig. (2-tailed)	0.195	0.289	0.243
Total Hip Z score	Pearson Correlation	-0.207	-0.136	-0.089
	Sig. (2-tailed)	0.273	0.474	0.640
Total Hip Z percent	Pearson Correlation	-0.206	-0.139	-0.116
	Sig. (2-tailed)	0.274	0.462	0.540
Ward Triangle BMD (g/ cm^2)	Pearson Correlation	-0.235	-0.274	-0.295
	Sig. (2-tailed)	0.210	0.142	0.113
Ward Triangle BMC (g)	Pearson Correlation	-0.235	-0.227	-0.124
	Sig. (2-tailed)	0.212	0.228	0.513
Ward Triangle Area (cm^2)	Pearson Correlation	0.138	0.186	0.245
	Sig. (2-tailed)	0.467	0.325	0.192

Pearson correlation coefficients and their corresponding p-values are shown.
AOD: Aerosol optical depth; PM: Particulate matters; BMD: Bone mineral density; BMC: Bone mineral content; GT: Greater trochanter; Inter: Inter trochanteric

Table 6. The correlation between particulate matters (PM) and aerosol optical depth (AOD) with lumbar bone parameters in patients with osteoporosis

		SMEAN [$PM_{2.5}$(µg/m^3)]	SMEAN [PM_{10}(µg/m^3)]	SMEAN(AOD)
L1_BMD (g/cm^2)	Pearson Correlation	-0.117	-0.077	-0.047
	Sig. (2-tailed)	0.352	0.543	0.708
L1_BMC (cm^2)	Pearson Correlation	-0.079	-0.010	0.043
	Sig. (2-tailed)	0.531	0.934	0.734
L1_Area (cm^2)	Pearson Correlation	-0.025	0.038	0.096
	Sig. (2-tailed)	0.844	0.761	0.446
L1_T_score	Pearson Correlation	-0.114	-0.073	-0.039
	Sig. (2-tailed)	0.367	0.563	0.755
L1_T_percent	Pearson Correlation	-0.041	-0.027	-0.025
	Sig. (2-tailed)	0.748	0.833	0.840
L1_Z_score	Pearson Correlation	-0.059	-0.035	-0.005
	Sig. (2-tailed)	0.644	0.781	0.971
L1_Z_percent	Pearson Correlation	-0.041	-0.010	0.031
	Sig. (2-tailed)	0.749	0.938	0.811
L2_BMD (g/cm^2)	Pearson Correlation	-0.060	-0.054	-0.103
	Sig. (2-tailed)	0.633	0.671	0.413
L2_BMC (g)	Pearson Correlation	-0.088	-0.010	0.066
	Sig. (2-tailed)	0.485	0.940	0.603
L2_Area (cm^2)	Pearson Correlation	0.040	0.109	0.185
	Sig. (2-tailed)	0.755	0.387	0.141
L2_T_score	Pearson Correlation	-0.088	-0.043	0.037
	Sig. (2-tailed)	0.485	0.733	0.767
L2_T_percent	Pearson Correlation	-0.181	-0.140	-0.103
	Sig. (2-tailed)	0.148	0.266	0.416
L2_Z_score	Pearson Correlation	-0.103	-0.066	-0.024
	Sig. (2-tailed)	0.417	0.607	0.852
L2_Z_percent	Pearson Correlation	-0.121	-0.086	-0.044
	Sig. (2-tailed)	0.342	0.499	0.729
L3_BMD (g/cm^2)	Pearson Correlation	-0.099	-0.045	-0.002
	Sig. (2-tailed)	0.431	0.725	0.986
L3_BMC (g)	Pearson Correlation	-0.010	0.045	0.071
	Sig. (2-tailed)	0.939	0.720	0.574
L3_Area (cm^2)	Pearson Correlation	0.060	0.104	0.161
	Sig. (2-tailed)	0.634	0.410	0.201
L3_T_score	Pearson Correlation	-0.107	-0.054	-0.011
	Sig. (2-tailed)	0.396	0.668	0.933
L3_T_percent	Pearson Correlation	-0.101	-0.051	-0.009
	Sig. (2-tailed)	0.424	0.686	0.942
L3_Z_score	Pearson Correlation	-0.042	0.008	0.094
	Sig. (2-tailed)	0.742	0.947	0.459
L3_Z_percent	Pearson Correlation	-0.008	0.027	0.059
	Sig. (2-tailed)	0.951	0.833	0.646
L4_BMD (g/cm^2)	Pearson Correlation	0.083	0.100	0.041
	Sig. (2-tailed)	0.512	0.426	0.748
L4_BMC (g)	Pearson Correlation	0.088	0.145	0.153
	Sig. (2-tailed)	0.488	0.248	0.225
L4_Area (cm^2)	Pearson Correlation	0.069	0.113	0.125
	Sig. (2-tailed)	0.583	0.371	0.319
L4_T_score	Pearson Correlation	0.073	0.094	0.043
	Sig. (2-tailed)	0.565	0.456	0.733
L4_T_percent	Pearson Correlation	0.094	0.109	0.044
	Sig. (2-tailed)	0.458	0.388	0.727
L4_Z_score	Pearson Correlation	0.134	0.146	0.086
	Sig. (2-tailed)	0.292	0.250	0.498
L4_Z_percent	Pearson Correlation	0.135	0.143	0.077
	Sig. (2-tailed)	0.288	0.260	0.547
Total BMD (g/cm^2)	Pearson Correlation	-0.079	-0.033	-0.019
	Sig. (2-tailed)	0.533	0.797	0.878
Total BMC (g)	Pearson Correlation	-0.021	0.054	0.106
	Sig. (2-tailed)	0.871	0.667	0.399
Total Area (cm^2)	Pearson Correlation	0.044	0.109	0.177
	Sig. (2-tailed)	0.729	0.386	0.158
Total T- score	Pearson Correlation	-0.085	-0.042	-0.025
	Sig. (2-tailed)	0.500	0.742	0.842
Total T- percent	Pearson Correlation	-0.072	-0.034	-0.028
	Sig. (2-tailed)	0.570	0.788	0.827
Total Z- score	Pearson Correlation	-0.004	0.031	0.045
	Sig. (2-tailed)	0.974	0.809	0.721
Total Z- percent	Pearson Correlation	0.005	0.035	0.041
	Sig. (2-tailed)	0.969	0.786	0.745

Pearson correlation coefficients and their corresponding p-values are shown.
AOD: Aerosol optical depth; PM: Particulate matters; BMD: Bone mineral density; BMC: Bone mineral content

In the osteoporosis subgroup, inverse correlations were observed between $PM_{2.5}$ and BMD, BMC, T-scores, and Z-scores in most femoral regions (neck, greater trochanter, intertrochanteric, total hip), except for the neck T-score. Similar inverse patterns were seen with PM_{10} and AOD across these parameters, except for the neck T-score. However, none of these correlations was statistically significant (Table 5).

The Correlation between PM and AOD with Lumbar Bone Parameters in Patients with Osteoporosis: Table 6 displays the relationship between PM with BMD, BMC, T-score, and Z-score in the lumbar spine of patients with osteoporosis.

Inverse correlations between $PM_{2.5}$ and BMD, BMC, T-scores, and Z-scores existed in different parts of the lumbar spine (total and L1-L3), but none were significant.

The Correlation between PM and AOD with Femur Bone Parameters in Patients with Osteoporosis: Table 5 displays the correlation between PM and AOD with femur bone parameters in patients with osteoporosis. In the osteoporosis subgroup, inverse correlations were observed between $PM_{2.5}$ and BMD, BMC, T-scores, and Z-scores in most femoral regions (neck, greater trochanter, intertrochanteric, total hip), except for the neck T-score. Similar inverse patterns were seen with PM_{10} and AOD across these parameters, except for the neck T-score.

However, none of these correlations was statistically significant (Table 5).

Discussion

Our study revealed that all patients in the osteoporosis group were over 50 years old.

The mean age of patients with osteoporosis was higher than that of the osteopenia and normal groups. This relationship was significant. The mean BMD, BMC, T-score, and Z-score of the femur and lumbar spine were significantly different across all three groups, with the lowest values observed in individuals with osteoporosis.

Our study also showed that there was no significant difference in the mean concentrations of $PM_{2.5}$, PM_{10}, and AOD on days when people (with normal BMD, osteopenia, and osteoporosis) were admitted to the bone densitometry department at Abadan Nuclear Medicine Center. In patients with osteoporosis, an inverse correlation existed between $PM_{2.5}$ and PM_{10} with BMD, BMC, T-score, and Z-score in different parts of the femur and lumbar spine. Still, none of the correlations was statistically significant.

Previous studies have reported conflicting results. Alvaer et al. found a weak but statistically significant inverse association between air pollution and total body BMD, but no significant association for total hip BMD (24). In our study, an inverse relationship was observed between PM and BMD in different parts of the femur (neck, greater trochanter, intertrochanteric, and total hip) although it was not statistically significant.

A 2015 study by Chen et al. found that living within 500m of a freeway was associated with lower total body and pelvic BMD, even after adjusting for age, sex, weight, height, body fat, and physical activity. Ambient air pollutants did not show a significant association with BMD. This study indicates that long-term exposure to traffic may contribute to the development of osteoporosis and its associated consequences (25).

Alver et al. found no link between air pollution and forearm fractures or BMD in men and women aged 59 and 60. A 10-unit increase in $PM_{2.5}$ was associated with a 64 mg/cm^2 decrease in distal forearm BMD due to long-term exposure. Long-term exposure to air pollution was not associated with bone health in women and men aged 59 and 60 (26).

The study by Lee et al. in 2014 found 45% higher odds of osteoporosis with a unit increase in NO_2. No significant association was observed with PM_{10}, ozone (O_3), sulfur dioxide (SO_2), and carbon monoxide (CO) for incident osteoporosis (27). A 2021 meta-analysis by Liu et al. found that exposure to air pollution, including $PM_{2.5}$ and NO_2, increased the risk of osteoporosis, specifically in total body BMD and hip fracture. However, there was no significant increase in the risk of osteoporosis regardless of exposure to PM_{10}, nitric oxide (NO), or O_3. There were no significant differences between exposure to PM_{10} and the risk of hip fracture, loss of total body BMD, or forearm fracture. There was no association between $PM_{2.5}$ increments and the risk of spine or forearm fractures (1). Our study found no significant association between PM_{10} and $PM_{2.5}$ levels and factors related to the femur and lumbar spine in patients with osteoporosis. However, we did not examine the effects of other pollutants such as O_3, SO_2, CO, and NO.

The 2022 study by Torkashvand et al. found a significant association between osteoporosis and PM_{10}; however, the relationship with $PM_{2.5}$ remains unclear. Particle materials indirectly cause osteoporosis and bone fractures by reducing the absorption of UV-B and vitamin D (7).

A 2021 study conducted by Shin et al. found that exposure to PM_{10} was associated with a higher incidence of osteoporosis in Korean adults aged 40 and above. The effect was more pronounced in women, those under 65 years old, and those living in less urban areas. However, exposure to NO_2, CO, SO_2, or $PM_{2.5}$ did not result in an increase in osteoporosis (28).

In 2020, Ranzani et al. conducted a cross-sectional analysis of a population-based cohort in a peri-urban area of South India and found that ambient air pollution was associated with lower BMD and BMC in young adults. Specifically, $PM_{2.5}$ exposure was linked to lower BMC in the spine and hip, as well as lower BMD in those areas (29).

According to Sung et al. study in 2020, there is evidence linking ambient exposure to PM with an increased risk of osteoporotic fractures. A PM level of less than 2.5 $\mu g/m^3$ was a risk factor, while PM_{10}/PM coarse/gaseous air pollutants (NO_2, SO_2, CO) showed no association (30).

Zhang et al. (2022) discovered that an increase of 10 $\mu g/m^3$ in $PM_{2.5}$ and SO_2 led to a corresponding decrease of 0.20 and 0.31, respectively, in the BMD T-score for the femoral neck. $PM_{2.5}$ increased osteoporosis prevalence by 5% per 1 $\mu g/m^3$ increment. $PM_{2.5}$ had a greater impact on osteoporosis. PM_{10} also elevated osteoporosis risk in rural populations by 4% per 1 $\mu g/m^3$ increase (8). Adami et al. in 2022 found a negative correlation between $PM_{2.5}$ exposure and T-score levels at the femoral neck and lumbar spine. Chronic exposure to $PM_{2.5}$ above 25 $\mu g/m^3$ led to a 16% higher risk of osteoporotic T-score at any site, while PM_{10} above 30 $\mu g/m^3$ led to a 15% higher risk. The femoral neck site was more susceptible to the negative effects of PM exposure than the lumbar spine site (11). Our study examined the relationship between PM_{10} and $PM_{2.5}$ levels with T-scores in different areas of the femur bone, revealing an inverse but non-significant correlation.

A study conducted by Qiao et al. in 2020 revealed that a 1 $\mu g/m^3$ increase in PM_1, $PM_{2.5}$, PM_{10}, and NO_2 was associated with a 14.9%, 14.6%, 7.3%, and 16.5% elevated risk of osteoporosis, respectively. It was estimated that 20.29%-24.36% of osteoporosis cases in the rural population of China could be attributed to air pollution, indicating that improving air quality could be beneficial (10). According to a 2022 study by Shi et al., higher levels of $PM_{2.5}$, PM_{10}, and NO_2 are positively associated with the incidence rate of hip fracture (IHF). On the other hand, O_3 levels exhibit a negative association. For every 5 $\mu g/m^3$ increase in $PM_{2.5}$, PM_{10}, and NO_2, the hip fracture rate increases by 9.5%, 9.2%, and 4.1%, respectively (13).

A 2021 review study by Pang et al. suggest a direct association between the severity and progression of osteoporosis and inflammation induced by air pollutants, such as PM. The current evidence does not provide conclusive results on the impact of PM exposure, including PM_1, $PM_{2.5}$, $PM_{2.5\text{-}10}$, and PM_{10}, on bone health and fracture incidence (5). Exposure to PM has been linked to a decline in bone health. Improving air quality, specifically reducing $PM_{2.5}$ concentrations, could lower the risk of bone fractures and improve bone health, especially among elderly women. Physical activity frequency may reduce the risk of osteoporotic fractures at high PM < 2.5 $\mu g/m^3$ (30).

The inconsistent findings from various studies regarding the relationship between PM exposure and BMD, as well as osteoporosis, may stem from differences in the climatic regions involved, the characteristics of the study participants, sample size, and the study designs used. Additional research and validation are necessary to conclusively determine the relationship between PM exposure and the risk of osteoporosis.

One of the strengths of our study, compared to other research, is that it examined the relationship between both PM_{10} and $PM_{2.5}$ with various bone parameters, including BMD, BMC, T-scores, and Z-scores. We analyzed these parameters in different parts of the femur (such as the neck, greater trochanter, intertrochanteric region, total hip, and Ward's triangle) as well as in the lumbar spine (L1-L4). This comprehensive approach allowed us to investigate three groups with differing bone densities: normal BMD, osteopenia, and osteoporosis, providing valuable insights.

Limitations: After comparing our study to others, we found conflicting results and uncertainties regarding the link between air pollution and BMD in patients with osteoporosis. Our study has several limitations, including a small sample size and a single-center design, which restricts the generalizability of the results to a broader population. Additionally, the number of male participants in our study was limited. Furthermore, we did not examine the association of other air pollutants, nor did we compare days with polluted air to those with clean air.

Recommendations: We recommend that future research investigate the association between BMD and PM in individuals with normal BMD, osteopenia, and osteoporosis in a larger population and a wider and more diverse range of locations. The study should also include a larger number of male participants. In addition, the effect of other airborne pollutants should also be investigated, and the study data should be compared between days with polluted and clean air.

Conclusion

Osteoporosis was associated with advanced age, female sex, and markedly reduced BMD parameters in the femur and lumbar spine. Besides, there was no significant relationship between the mean concentration of $PM_{2.5}$ and PM_{10} and the parameters of BMD, BMC, T-score, and Z-score in the bones of the femur and spine of patients with osteoporosis.

Conflict of Interest

The authors declare no conflict of interest in this study.

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