

Impact of Aging on Bone Microarchitecture and Mechanical Strength

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ABOVE THE STUDY

Aging is a major determinant of skeletal health, profoundly influencing bone microarchitecture and mechanical strength. These changes contribute significantly to the increased incidence of fragility fractures observed in elderly populations. While Bone Mineral Density (BMD) has traditionally been used as a clinical indicator of bone health, it does not fully capture the structural and material alterations that occur with aging. Therefore, a deeper understanding of age-related changes in bone microarchitecture is essential for improving fracture risk assessment and developing targeted therapeutic strategies.

Bone is a hierarchical tissue composed of cortical (compact) and trabecular (spongy) compartments, each contributing to overall mechanical competence. With advancing age, both compartments undergo significant deterioration. Trabecular bone experiences a reduction in trabecular number and thickness, along with increased separation, leading to a more porous and fragile structure [1]. These microstructural changes compromise the bone's ability to distribute mechanical loads efficiently, thereby increasing susceptibility to fractures [2].

Cortical bone is not spared from age-related degeneration. Aging is associated with increased cortical porosity, primarily due to enhanced intracortical remodeling and the expansion of Haversian canals [3]. This porosity reduces bone stiffness and strength, even in individuals with relatively preserved BMD [4]. Importantly, the combined deterioration of trabecular and cortical compartments results in a cumulative decline in bone quality that cannot be adequately explained by bone mass alone.

At the cellular level, aging disrupts the balance between bone formation and resorption. Osteoblast function declines with age, partly due to reduced proliferation and differentiation of mesenchymal stem cells [5]. In contrast, osteoclast activity may remain stable or even increase, leading to a net loss of bone mass. Additionally, age-related oxidative stress and chronic low-grade inflammation further impair osteoblast function and promote osteoclastogenesis [6]. These cellular changes are key drivers of the observed microarchitectural deterioration. Mechanical strength of bone is influenced not only by its structure but also

by its material properties. Aging affects the composition and organization of bone matrix, including changes in collagen cross-linking and mineralization. Non-enzymatic glycation of collagen leads to the accumulation of Advanced Glycation End products (AGEs), which reduce bone toughness and increase brittleness [7]. Moreover, alterations in mineral crystal size and distribution can further compromise the mechanical integrity of bone [8].

Recent advances in imaging technologies, such as High-Resolution Peripheral Quantitative Computed Tomography (HR-pQCT), have enabled detailed assessment of bone microarchitecture in vivo. These tools have revealed that microstructural deterioration begins earlier than previously thought and progresses with age, even in the absence of significant changes in BMD [9]. Such findings underscore the importance of incorporating microarchitectural parameters into clinical evaluation and fracture risk prediction models. From a clinical perspective, the impact of aging on bone quality has significant implications for the management of osteoporosis and related disorders. Current therapeutic strategies, including antiresorptive and anabolic agents, aim to restore the balance of bone remodeling. However, their effects on microarchitecture and material properties vary, and long-term outcomes remain an area of active investigation [10]. Preventive measures, such as adequate nutrition, physical activity, and fall prevention, are also critical in mitigating age-related bone loss.

In conclusion, aging exerts a multifaceted impact on bone microarchitecture and mechanical strength, involving structural, cellular, and material changes. These alterations collectively compromise bone quality and increase fracture risk. A comprehensive approach that goes beyond BMD to include microarchitectural and biomechanical assessments is essential for improving diagnosis and treatment of age-related bone disorders.

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