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BONE STRENGTH AND TECHNIQUES OF ASSESSMENT

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Abstract:
Bone plays a vital role in providing structural support, protecting internal organs, storing minerals, and regulating metabolic and endocrine functions. Bone strength depends on both cortical and trabecular components, which vary in proportion across different skeletal sites. With aging, remodeling imbalances lead to bone loss, microarchitectural deterioration, and osteoporosis—a silent disease often first recognized after fragility fractures. Early detection is crucial to reduce morbidity and healthcare burden. This review discusses current and emerging techniques for assessing bone health and strength. Dual-energy X-ray absorptiometry (DEXA) remains the gold standard for measuring bone mineral density (BMD), although it is influenced by patient positioning, soft tissue composition, and prior fractures. Quantitative computed tomography (QCT), including peripheral and high-resolution variants (pQCT, HR-pQCT), provides three-dimensional assessment and detailed evaluation of trabecular microarchitecture, improving fracture risk prediction. Magnetic resonance imaging (MRI) and spectroscopy offer radiation-free assessment of bone quality, while quantitative ultrasound provides a low-cost, portable screening tool. Emerging modalities such as finite element analysis, electromechanical impedance, microwave frequency methods, and machine learning algorithms show promise for individualized risk assessment and real-time monitoring. Despite these advances, limitations in accessibility, cost, and standardization remain. Integrating these technologies into clinical practice may enhance early diagnosis, optimize treatment strategies, and improve outcomes in patients at risk for osteoporosis and fractures.

Keywords- bone strength, DEXA, BMD

Introduction

Bones play a diverse role in the body, ranging from providing structural support and protection for internal organs, storage of minerals such as calcium and phosphate, and producing hormones to regulate mineral and energy metabolism. Bones have a variable proportion of cortical tissue (often 80%) and trabecular tissue (often 20%), which are involved in supporting the bone strength. Long bones have a greater proportion of cortical tissue, and vertebrae contain more trabecular bone. *(1-5)* Bones undergo a continuous remodeling process by the sequential process of resorption and regeneration. But over a period of time, microdeficits in the replacement of bones in the process of remodeling lead to thinning of the bones and development of osteoporosis and microarchitectural deterioration of the tissue. Osteoporosis is associated with increased bone fragility and susceptibility to fracture. In men, after the age of 20 years, bone resorption becomes predominant, and the mineral content of the bones declines by about 4% over a decade. *(6)* Females usually maintain the peak mineral content up to menopause, and then the bone mineral content declines by about 15% per decade. *(6)* Multiple risk factors have been identified for osteoporosis, such as aging, smoking, intake of corticosteroids, improper diet, sedentary lifestyle, and intake of certain drugs, such as immunosuppressant drugs. *(6-9)*

Osteoporosis is a silent disease and may first manifest when the patient develops a fracture after a trivial trauma. Such fractures lead to chronic health problems. Screening of the population patients to find out the high-risk population who will require treatment (calcium and vitamin D, other drugs) may reduce the social and economic burden.

Multiple methods of screening have been developed over the years. This review gives an insight about different methods for the evaluation of bone health and the diagnosis of osteoporosis.

Dual-energy X-ray absorptiometry (DEXA)

DXA is considered the gold standard for measuring bone mineral density (BMD) globally. DXA systems generate X-ray beams of two different levels of energy, namely: high (e.g., 71 keV) and low energy levels (e.g., 39 keV). The absorption of the high and low-energy beams by the diverse body tissues helps to quantify BMD. Bone minerals, such as calcium, absorb more low-energy X-ray beams than soft tissues. The attenuation imposed by soft tissues on the X-ray beams in body regions without bones is used as a baseline measurement. Bone mineral content is then calculated by subtracting the attenuation ratio between low and high-energy X-rays through tissue and bone from the baseline measurement. An X-ray sweep can be performed on the region of interest in order to provide images. Bone density values are reported as standard deviation units in comparison to normal control values in the form of the T-score. The reference values for normal subjects, low bone density (osteopenia), and osteoporosis are, respectively: T-score -1, T-score -1 to -2.5, and T-score -2.5.

BMD should be measured from the posterior-anterior spine (L1 to L4, excluding those with structural damage) and hip (the lowest BMD value between the proximal femur or femoral neck). In case of hyperparathyroidism or obesity, BMD may be measured from the forearm (1/3 distal radius).

BMD measurements in children who have not achieved their peak bone mass are carried out by means of the Z-score. The Z-score can be calculated. *(10)*

Measurement of BMD must be performed from the posterior-anterior spine (L1 to L4, excluding those with structural damage) and hip (the lowest BMD value between the proximal femur or femoral neck). In patients with hyperparathyroidism or obesity, BMD may be measured from the forearm (1/3 distal radius). *(11-17)*

Advantages- DEXA can provide an integrated examination of cortical and trabecular bone, which is frequently practiced in routine practice. *(1)*

Limitations

BMD measured by DEXA is only one aspect of the complex understanding of bone quality. Several factors can adversely affect the accuracy of the DEXA technique. These include the process of preparation, the surrounding soft tissue and its composition, and the scanning conditions. *(1)*

In patients with a fragility fracture, a lumbar vertebra compressed by a fragility fracture may generate a measurement artifact. The T-score may exhibit racial variations. BMD is considered to be more suitable for monitoring patients. DEXA requires trained operators since correct patient positioning is important. Quality control procedures must be followed to ensure repeatability of DXA measurements. Such features could hamper the follow-up of patients' treatment. *(13-17)*

Quantitative computed tomography (QCT)

During the procedure of QCT, the X-ray beam and detectors are rotated around the patient during the exam. QCT generates cross-sectional images after processing multiple X-ray planes acquired at different body angles and in the area of interest. QCT is generally obtained from the lumbar spine and hip (other bones include the proximal femur, forearm, and tibia) by use of standard whole-body CT scanners and dedicated software. QCT plays an important role in osteoporosis diagnosis since it provides selective trabecular BMD measurement (tissue more affected by metabolic diseases) and has superior soft tissue differentiation. *(18-21)*

Advantages-

QCT and HR-pQCT scans are a reliable and accurate technique. They give valuable and comprehensive insight into bone quality. *(1)* QCT is considered to be a better predictor for the mechanical strength of the intertrochanteric region with a high degree of precision. QCT provides selective trabecular BMD measurement and has superior soft tissue differentiation. Microstructural measurements and mechanical characteristics of the distal tibia can be obtained from HR-pQCT images. HR-pQCT could also be a useful tool for assessing the fracture healing process. pQCT has other advantages, such as measuring bone density independently of overlying tissue, less interference due to bone size, being relatively safe, higher accuracy, and 3D visualization. The second-generation HR-pQCT has been improved to 61 μm, giving a more accurate assessment of trabecular thickness. *(1,18-21)*

Micro-computed tomography (Micro-CT, μCT)

Peripheral QCT (pQCT) requires the application of QCT to appendicular skeleton sites, such as arms or legs. In comparison with general CT scanners, pQCT devices have similar data acquisition and reconstruction procedures, but they have the advantages of greater mobility, less radiation, and lower cost. *(22,23)* High-resolution pQCT (HR-pQCT) helps obtain a more detailed follow-up of patients under treatment compared to DXA. HR-pQCT can be used to analyze subchondral trabecular bone in patients with medial knee osteoarthritis. Assessment of trabecular bone architecture and BMD at the distal radius and tibia by HR-pQCT gives reproducible results and can also detect aging and disease-related changes. *(22,23)* Recently, finite element (FE) models and pQCT have been used to compute bone strength and stiffness of the forearm (i.e., distal radius). FE modelling allows the assessment of osteoporotic bone strength and can be useful to identify patients with peripheral low-trauma fractures. Therefore, pQCT-FE is considered to enhance the diagnosis when compared to standard pQCT and DXA. *(22,23)*

Magnetic Resonance Imaging (MRI)

MRI images to characterize vertebral fragility or fracture from pre-processed images, and they are segmented, before having the features extracted and classified. Further development of these methods could improve may screening of osteoporosis.

Advances in MRI technology have facilitated the inclusion of magnetic resonance spectroscopy (MRS) in the investigation of organ metabolism.

MRI does not expose the patient to ionizing radiation. But MRI is an expensive and time-consuming investigation. Techniques for its application to characterize bones are being further developed. *(24)*

Overview of current technologies used to study bone mineral density

Technology	Advantages / Current place	Limitations
DEXA Based on X-rays	Gold standard for diagnosis	Requires rigorous quality control procedures Expensive, large, and bulky

		Inaccurate measurements in bones previously fractured Patients are exposed to ionizing radiation Large racial diversity in comparative values Questionable adequacy for follow-up
Quantitative-Computed Tomography Based on X-rays Multiple cross-sectional images are generated Analyses of quantitative parameters	Less susceptible to confounding factors Greater sensitivity than DXA	Exposure to ionizing radiation High cost and low availability The scanning procedure is complex and requires training
Peripheral QCT Computed Tomography-based method Applied to appendicular skeleton sites	Less bulky, less expensive, lower radiation, and higher mobility than QCT Facilitates follow-up	Expensive Patients are exposed to ionizing radiation
Magnetic Resonance Imaging Images based on RF signals emitted by hydrogen atoms excited by magnetic fields	Ionizing radiation-free	Expensive
Quantitative Ultrasound Piezoelectric transducers Assesses the properties of ultrasound waves applied to the bones	Low cost and portable Useful for screening	Not suitable for diagnosis or for follow-up

Emerging technologies: capabilities and limitations.

Technology	Advantages	Limitations
Electromechanical Impedance • Based on the principle of measurement of electrical impedance • Use low-cost PZT patches	• No risk of ionizing radiation free • Low cost • Portable • Easy handling	Results are not consistent Limitation to place the PZT patch on bones

• Needs a baseline reference measurement		
Stimulus Response Based on the vibration theory Measures bone response resulting from mechanical stimulus	• Ionizing radiation-free • Low cost • Portable • Easy handling	Results are not consistent
Microwave frequency Based on the principle of radio wave propagation Uses on-body antennas Applied to the wrist	• Ionizing radiation-free Low radiated power (0.1 W) • No need for coupling media • Easy handling • Fast response (2030s)	Will need more clinical studies
Machine Learning • Based on computer algorithms • Extracts and classifies patterns	Assesses clinical risk factors Classifies patterns without human intervention Analyzes other techniques' measurements	Results and interpretations are affected by quality of data input Affected by coding quality

Conclusion

Osteoporosis is a silent disease. It can have severe effects on the quality of life of the patient. Early diagnosis is essential in order to initiate the appropriate preventive measures in these patients. Advanced techniques now have an important role to play in the screening of populations and patients for bone morphology and microarchitecture. The emerging testing methods have been designed to overcome the drawbacks of the earlier generation of bone health assessment methods. However, in the era of machine learning, we still need large studies to be conducted with new diagnostic techniques to be able to adopt them the the routine practice in the real world setting.

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