QUANTITATIVE BONE ULTRASONOGRAPHY AND QUANTITATIVE COMPUTED TOMOGRAPHY AS ALTERNATIVE METHODS TO BONE DENSITOMETRY IN THE DIAGNOSIS OF OSTEOPOROSIS

ULTRASSONOGRAFIA ÓSSEA QUANTITATIVA E TOMOGRAFIA COMPUTADORIZADA QUANTITATIVA COMO MÉTODOS ALTERNATIVOS À DENSITOMETRIA ÓSSEA NO DIAGNÓSTICO DA OSTEOPOROSE

ULTRASONOGRAFÍA ÓSEA CUANTITATIVA Y TOMOGRAFÍA COMPUTARIZADA CUANTITATIVA COMO MÉTODOS ALTERNATIVOS A LA DENSITOMETRÍA ÓSEA EN EL DIAGNÓSTICO DE LA OSTEOPOROSIS

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ABSTRACT

Osteoporosis is a chronic osteometabolic disease characterized by a reduction in bone mineral density and deterioration of the microarchitecture of bone tissue, resulting in a significant increase in the risk of fractures, especially in the elderly and in postmenopausal women. As it is a silent condition, early diagnosis is essential for the prevention of clinical and socioeconomic complications. Currently, dual-energy X-ray absorptiometry (DEXA) is considered the gold standard for assessing bone mineral density; however, it presents limitations related to cost, availability, the influence of artifacts, and the inability to evaluate in detail the structural quality of bone. In this context, the document analyzes quantitative bone ultrasonography (QUS) and quantitative computed tomography (QCT) as alternative and complementary methods to DEXA in the diagnosis of osteoporosis. QUS stands out for being a portable, low-cost method free of ionizing radiation, allowing its application in population screenings and in locations with limited infrastructure. Through the analysis of parameters such as speed of sound (SOS), broadband ultrasound attenuation (BUA), and composite indices, QUS provides functional information about bone quality and fracture risk, being especially useful as an initial screening tool. QCT, in turn, enables the three-dimensional and volumetric measurement of bone mineral density, expressed in mg/cm³, allowing the differentiation between cortical and trabecular bone. This characteristic provides greater sensitivity for the early detection of structural changes, especially in the trabecular

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bone of the lumbar spine and hip, which are often affected in the early stages of osteoporosis. Despite its high diagnostic accuracy, QCT presents important limitations, such as higher radiation dose, high cost, and lower availability, restricting its routine use in clinical practice and directing it mainly to specific or research contexts. It is concluded that, although DEXA remains the reference method for the diagnosis of osteoporosis, QUS and QCT play relevant roles as complementary techniques, expanding the capacity for assessing bone health. The integration of these methods may contribute to earlier, more accessible, and more accurate diagnoses, favoring more effective preventive and therapeutic strategies in the management of osteoporosis.

Keywords: Osteoporosis. Bone Densitometry. Bone Ultrasonography and Computed Tomography.

RESUMO

A osteoporose é uma doença osteometabólica crônica caracterizada pela redução da densidade mineral óssea e pela deterioração da microarquitetura do tecido ósseo, resultando em aumento significativo do risco de fraturas, especialmente em idosos e mulheres após a menopausa. Por ser uma condição silenciosa, o diagnóstico precoce é essencial para a prevenção de complicações clínicas e socioeconômicas. Atualmente, a densitometria óssea por dupla emissão de raios X (DEXA) é considerada o padrão ouro para avaliação da densidade mineral óssea; contudo, apresenta limitações relacionadas ao custo, à disponibilidade, à influência de artefatos e à incapacidade de avaliar de forma detalhada a qualidade estrutural do osso. Nesse contexto, o documento analisa a ultrassonografia óssea quantitativa (UOQ) e a tomografia computadorizada quantitativa (TCQ) como métodos alternativos e complementares à DEXA no diagnóstico da osteoporose. A UOQ destaca se por ser um método portátil, de baixo custo e isento de radiação ionizante, permitindo sua aplicação em triagens populacionais e em locais com infraestrutura limitada. Por meio da análise de parâmetros como velocidade do som (SOS), atenuação de banda larga (BUA) e índices compostos, a UOQ fornece informações funcionais sobre a qualidade óssea e o risco de fraturas, sendo especialmente útil como ferramenta de rastreamento inicial. A TCQ, por sua vez, possibilita a mensuração tridimensional e volumétrica da densidade mineral óssea, expressa em mg/cm³, permitindo a diferenciação entre osso cortical e trabecular. Essa característica confere maior sensibilidade para a detecção precoce de alterações estruturais, principalmente no osso trabecular da coluna lombar e do quadril, frequentemente afetado nas fases iniciais da osteoporose. Apesar de sua alta precisão diagnóstica, a TCQ apresenta limitações importantes, como maior dose de radiação, custo elevado e menor disponibilidade, restringindo seu uso rotineiro à prática clínica e direcionando a principalmente a contextos específicos ou de pesquisa. Conclui se que, embora a DEXA permaneça como método de referência para o diagnóstico da osteoporose, a UOQ e a TCQ desempenham papéis relevantes como técnicas complementares, ampliando a capacidade de avaliação da saúde óssea. A integração desses métodos pode contribuir para diagnósticos mais precoces, acessíveis e precisos, favorecendo estratégias preventivas e terapêuticas mais eficazes no manejo da osteoporose.

Palavras-chave: Osteoporose. Densitometria Óssea. Ultrassonografia Óssea e Tomografia Computadorizada.

RESUMEN

La osteoporosis es una enfermedad osteometabólica crónica caracterizada por la reducción de la densidad mineral ósea y el deterioro de la microarquitectura del tejido óseo, lo que resulta en un aumento significativo del riesgo de fracturas, especialmente en personas mayores y mujeres posmenopáusicas. Al ser una condición silenciosa, el diagnóstico precoz

es esencial para la prevención de complicaciones clínicas y socioeconómicas. Actualmente, la densitometría ósea por absorciometría de rayos X de doble energía (DEXA) se considera el estándar de oro para la evaluación de la densidad mineral ósea; sin embargo, presenta limitaciones relacionadas con el costo, la disponibilidad, la influencia de artefactos y la incapacidad de evaluar de forma detallada la calidad estructural del hueso. En este contexto, el documento analiza la ultrasonografía ósea cuantitativa (UOC) y la tomografía computarizada cuantitativa (TCC) como métodos alternativos y complementarios a la DEXA en el diagnóstico de la osteoporosis. La UOC se destaca por ser un método portátil, de bajo costo y libre de radiación ionizante, permitiendo su aplicación en cribados poblacionales y en lugares con infraestructura limitada. Mediante el análisis de parámetros como la velocidad del sonido (SOS), la atenuación ultrasónica de banda ancha (BUA) y los índices compuestos, la UOC proporciona información funcional sobre la calidad ósea y el riesgo de fracturas, siendo especialmente útil como herramienta de cribado inicial. Por su parte, la TCC permite la medición tridimensional y volumétrica de la densidad mineral ósea, expresada en mg/cm³, posibilitando la diferenciación entre hueso cortical y trabecular. Esta característica confiere mayor sensibilidad para la detección precoz de alteraciones estructurales, especialmente en el hueso trabecular de la columna lumbar y la cadera, frecuentemente afectado en las etapas iniciales de la osteoporosis. A pesar de su alta precisión diagnóstica, la TCC presenta limitaciones importantes, como mayor dosis de radiación, alto costo y menor disponibilidad, restringiendo su uso rutinario en la práctica clínica y dirigiéndolo principalmente a contextos específicos o de investigación. Se concluye que, aunque la DEXA permanece como método de referencia para el diagnóstico de la osteoporosis, la UOC y la TCC desempeñan papeles relevantes como técnicas complementarias, ampliando la capacidad de evaluación de la salud ósea. La integración de estos métodos puede contribuir a diagnósticos más precoces, accesibles y precisos, favoreciendo estrategias preventivas y terapéuticas más eficaces en el manejo de la osteoporosis.

Palabras clave: Osteoporosis. Densitometría Ósea. Ultrasonografía Ósea y Tomografía Computarizada.

1 INTRODUCTION

Osteoporosis is a metabolic bone disease characterized by a progressive reduction in mineral density and deterioration of the microarchitecture of bone tissue, resulting in greater fragility and risk of fractures (SOZEN; OZISIK; BASARAN, 2017). It is a silent disease, which often remains asymptomatic until fractures occur, which reinforces the importance of early diagnosis. It is estimated that osteoporosis affects millions of people worldwide, being more prevalent in women after menopause, due to reduced estrogen levels and increased bone resorption (SANTOS et al., 2019).

Early diagnosis is essential for the prevention of complications and for the proper management of the disease. Currently, the method considered the gold standard for assessing bone mineral density is dual-energy X-ray bone densitometry (DEXA), capable of accurately measuring bone density in specific regions of the body, such as the lumbar spine and femur (GENANT et al., 2019). However, despite its accuracy and wide use, the test has some limitations, such as the high cost of the equipment, the need for adequate infrastructure, and the restriction of access in places with few technological resources, in addition to not differentiating cortical and trabecular bone (ENGELKE et al., 2015).

Given these limitations, there is growing interest in alternative and complementary diagnostic methods to DEXA. Among the main techniques under study, quantitative bone ultrasonography (UOQ) and quantitative computed tomography (QCT) stand out, both of which are capable of assessing bone mineral density using different physical principles and with different advantages (MOAYYERI et al., 2015). UOQ has proven to be a promising option because it is a portable, low-cost method free of ionizing radiation, which facilitates its application in population screenings and in places with limited access to sophisticated equipment (LI et al., 2022). On the other hand, QCT allows a three-dimensional and volumetric evaluation of bone tissue, offering more detailed information about trabecular and cortical structure, with the potential to identify changes in earlier stages (ENGELKE et al., 2015)

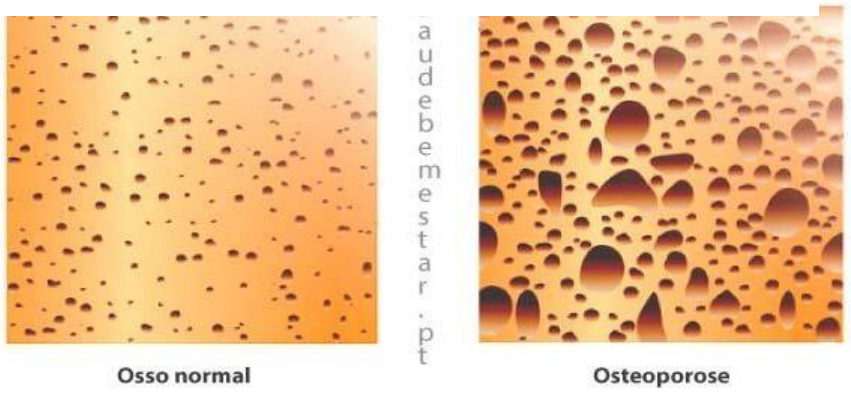
The relevance of this study lies in the need to expand knowledge about alternative methods to bone densitometry, in order to support a more accessible and effective clinical practice. Understanding the advantages, limitations, and indications for the use of UOQ and QCT is essential to strengthen the performance of the radiology technologist, contributing to a broader and more humanized diagnosis of osteoporosis. In addition, the constant technological evolution in the field of medical imaging reinforces the importance of reviews that evaluate the diagnostic performance of these techniques, considering aspects such as cost-benefit, availability, and clinical applicability (NORD et al., 2020).

2 OSTEOPOROSIS AND THE NEED FOR BONE STRUCTURE ASSESSMENT

Osteoporosis is a chronic metabolic and osteometabolic disease characterized by the progressive reduction of bone mineral density (BMD) and the deterioration of trabecular and cortical microarchitecture, compromising the mechanical strength of the bone and significantly increasing the risk of fractures. The representation of healthy bone and bone with osteoporosis is shown in Figure 1. This deterioration results from an imbalance between bone formation and resorption, a process intensified by aging, hormonal changes, especially after menopause, and clinical conditions or external factors. Because it is a silent and asymptomatic disease until fractures occur, its early identification is essential for the prevention of complications and for the proper management of bone health (COLÓN-EMERIC; NAPOLI, 2020; SOZEN; OZISIK; BASARAN, 2017).

Figure 1

Illustration of healthy and osteoporotic bone



Source: HEALTH WELL-BEING. Bone densitometry or bone osteodensitometry (2019).

The diagnostic identification of osteoporosis traditionally follows the criteria of the World Health Organization (WHO), which considers a T-score equal to or less than -2.5 standard deviation, obtained by bone densitometry, as indicative of established disease. However, recent studies have shown that factors beyond mineral density, such as collagen quality, trabecular integrity, and bone microarchitecture, also have a determining influence on fracture risk. Thus, BMD assessment remains essential, but there is a growing need for diagnostic methods capable of analyzing bone in a more comprehensive way, contemplating structural and biomechanical aspects that traditional densitometry does not fully capture (WHO, 2019; DELBET et al., 2019).

The clinical and epidemiological relevance of osteoporosis stems not only from its high prevalence, but mainly from the fractures associated with the disease, which represent an important cause of morbidity, functional disability, loss of autonomy, and increased

mortality among adults and the elderly. It is estimated that one in three women and one in five men over 50 years of age will suffer an osteoporotic fracture throughout their lives, with the hip, spine and wrist being the most frequently affected sites. Hip fractures have a mortality rate of up to 30% in the first year, in addition to high rates of rehospitalization and institutionalization, constituting a serious public health problem (KANIS et al., 2020; CUMMINGS et al., 2018).

The impact of osteoporosis transcends the biomedical field, reaching expressive social and economic dimensions. The continuous increase in life expectancy and the growth of the elderly population project a significant increase in the number of fractures in the coming decades. This scenario reinforces the need for more efficient, accessible, and sensitive diagnostic strategies that allow identifying individuals at risk before the first fracture occurs. In this context, it is essential to understand the characteristics, potentialities, and limitations of the different bone evaluation methods, including bone densitometry (DEXA), quantitative bone ultrasonography (UOQ), and quantitative bone tomography (QCT), which improve diagnostic accuracy and expand the ability to detect the disease early (SANTOS et al., 2019; DELBET et al., 2019).

Thus, understanding osteoporosis in its pathophysiological, clinical, epidemiological and diagnostic complexity is essential to improve prevention, follow-up and treatment strategies. The assessment of bone density and quality remains one of the central pillars in coping with the disease, justifying the deepening of the study of the available diagnostic methods and their clinical applications today (SANTOS et al., 2019; DELBET et al., 2019).

3 DIAGNOSTIC METHODS OF OSTEOPOROSIS

3.1 BONE DENSITOMETRY (DEXA)

Bone is a living structure that needs constant monitoring to avoid silent fractures, bone densitometry by dual-energy X-ray absorptiometry, known as DEXA or DXA, is one of the methods to perform this monitoring (PADI, 2023). Developed in the 1960s and perfected in the 1980s, it has become the World Health Organization's (WHO) gold standard for diagnosing osteoporosis, a disease that affects millions in Brazil, especially postmenopausal women. The current densitometers are presented in the configuration shown in figure 2 (BRASIL, 2022).

Figure 2

Hologic Discovery bone densitometer, consisting of a scanning table and computerized workstation

Source: Hologic (2023).

DEXA measures bone mineral density (BMD), expressed in grams per square centimeter (g/cm²), focusing on critical regions such as the lumbar spine (vertebrae L1 to L4), the neck of the proximal femur and the distal radius, sites with a higher risk of fracture (FLEURY, n.d.). This test has high reproducibility, with BMD measurement ranging from around 1% to 2% in successive tests in the same patient, which allows the detection of small and real variations in bone density, i.e., DEXA can identify changes in BMD with a very small margin of error, ensuring reliability in the follow-up of osteoporosis progression or in response to treatment (PADI, 2023).

Regarding radiation, DEXA uses a very low effective dose, between 2 to 10 microsieverts (μSv), which is roughly equivalent to the natural radiation a person receives in a day or two outdoors due to exposure to natural sources such as the sun. (PADI, 2023). For comparison, a common chest X-ray exam usually exposes the patient to a dose between 100 and 200 μSv, that is, about 10 to 100 times higher than a bone densitometry exam, which makes DEXA a safe technique and indicated for repeated evaluation and clinical monitoring of bone health (BRONSTEIN, 2023).

This technique is essential because osteoporosis progresses without symptoms until the fracture occurs, and DEXA allows early screening in risk groups: women over 65 years old, men over 70, or those who have factors such as smoking, corticosteroid use, or family history (BRASIL, 2022). In the SUS and private clinics, she guides therapeutic decisions, monitoring improvements over time. However, artifacts due to calcifications or implants can falsify results, making room for alternative methods (ASSOCIAÇÃO BRASILEIRA DE RADIOLOGY, 2019).

3.1.1 How DEXA works

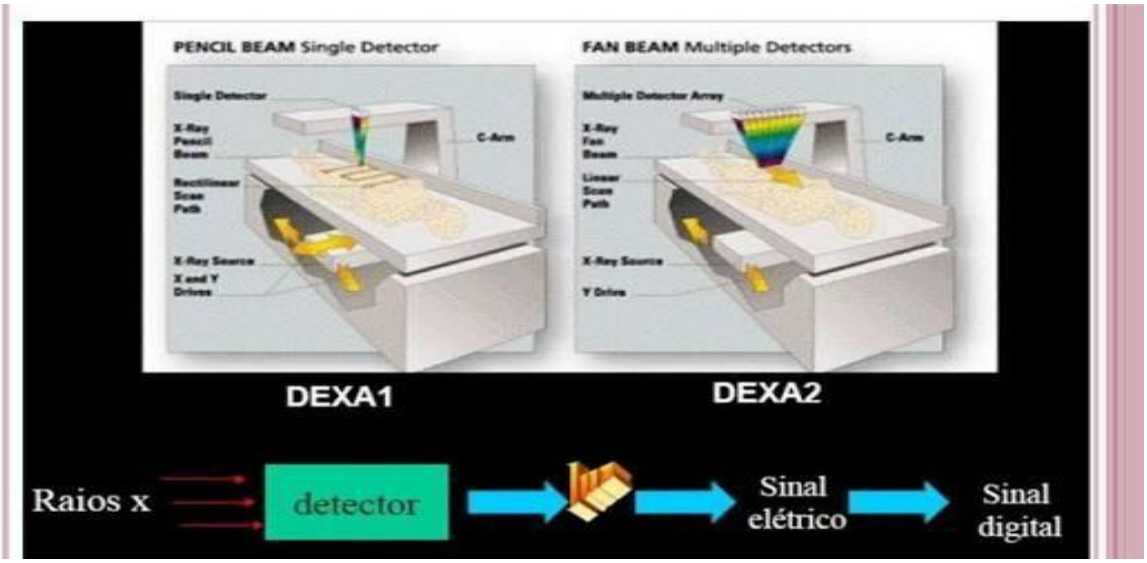
Dual-energy bone densitometry (DEXA) is based on differential attenuation of X-rays with two distinct energies as they pass through tissues, allowing the separate quantification of bone mineral density in relation to adjacent soft tissues (RADIOLOGIA TANNUS, n.d.). The examination is performed with an X-ray tube that emits an X-ray beam with two energy levels, usually around 70 kVp (low energy) and 140 kVp (high energy), whose difference in absorption by soft tissues and mineralized bone allows the calculation of bone mineral density (BMD) in regions of interest. These bundles cross the body simultaneously, but interact differently with the tissues. The low-energy beam is more strongly absorbed by the bone, which is denser and contains minerals, resulting in greater attenuation of this beam as it passes through bone tissue. The high-energy beam, on the other hand, is less affected by bone and penetrates more easily through soft tissues, such as muscles and fat, which have a lower density. This difference in attenuation between the two bundles allows the computer system to specifically isolate and calculate bone mineral density by subtracting the contribution of soft tissues. Thus, DEXA can accurately measure bone density separated from the rest of the tissues. (PADI, 2023).

Semiconductor or scintillation detectors, positioned on the other side of the patient, capture this remaining radiation. Sophisticated software does the math: it subtracts the attenuation of the soft tissues (calculated by the difference between the bundles) and isolates the BMD from the bone. The basic formula is something like BMD = (Atenuação_alta - Atenuação_baixa) / estimated tissue thickness, all processed in seconds (FLEURY, n.d.). There are two main modes: the "*pencil-beam*" (thin, slower, but precise beam for the spine) and the "*fan-beam*" (wide, fast full-body fan, in 5-15 minutes). The two beam modes are represented in figure 4. The patient lies motionless on a motorized table, with legs fixed to prevent movement, a crucial detail, as vibrations invalidate the exam (BRONSTEIN, 2023).

Technical standards, such as those of the Brazilian Society of Radiology, require daily calibration with phantoms (bone simulators) to ensure reproducibility. This simple but ingenious engineering makes DEXA efficient and safe (ASSOCIAÇÃO BRASILEIRA DE RADIOLOGY, 2019).

Figure 3

Scheme of X-ray beam systems in DEXA (pencil beam vs fan beam)



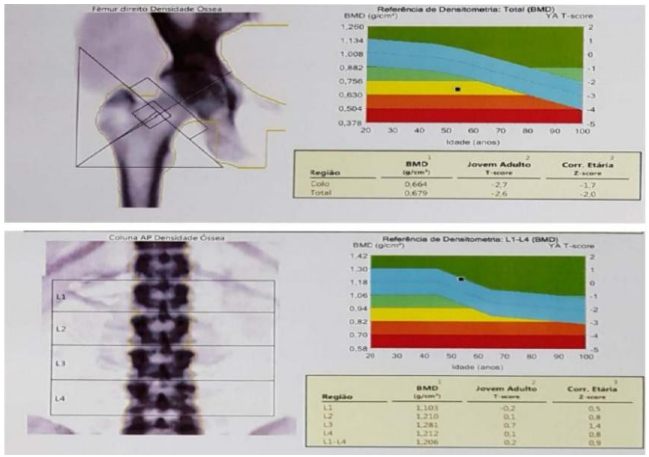
Source: REIS, Silvana (2021).

3.1.2 DEXA Generated Diagnosis

Interpretation of DEXA results transforms numerical bone mineral density values into a clinical diagnosis. After the scan, the report appears as a color map, with delimited regions of interest (ROI) — standardized squares over L1-L4, femoral neck, and radius, as shown in figure 4 (SABIN, 2025). Crude BMD (g/cm²) is converted into comparative scores: the T-score, which measures standard deviations (SD) in relation to peak bone mass in healthy young adults (20-30 years); and the Z-score, adjusted for age, sex, and ethnicity (PADI, 2023).

Figure 4

Interface of a workstation monitor after a bone densitometry examination of the lumbar spine and femur



Source: LINS, Bia (2024).

The interpretation of the DEXA results is based on the T-score, with values ≥ -1.0 considered normal, between -1.0 and -2.5 indicative of osteopenia and ≤ -2.5 diagnosis of osteoporosis, with an increased risk of fracture in sites such as the spine and hip (BRASIL, 2022). This classification, together with reference graphs and risk stratification tools such as FRAX, which incorporate BMD and clinical factors (age, BMI, diabetes, smoking, etc.), allows a more complete assessment of fracture risk in 10 years (FLEURY, n.d.).

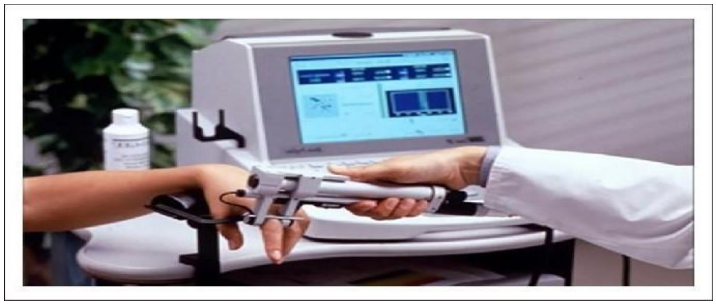
However, DEXA has relevant limitations: arthrosis in the spine can artificially raise BMD; obesity (BMI > 30 kg/m²) may underestimate BMD in the femur; and the presence of metal prostheses or implants generates artifacts that compromise the analysis (PADI, 2023). In these situations, the priority should be to read less affected sites, such as the distal radius, or to use complementary methods, such as quantitative bone ultrasound (UOQ) and quantitative computed tomography (QCT), for a more reliable assessment of bone health (PADI, 2023). DEXA is essential for the diagnosis of osteoporosis and the follow-up of the response to treatment, but it does not identify the causes of bone loss, which depend on clinical and laboratory evaluation and, in some cases, investigation of systemic diseases (ASSOCIAÇÃO BRASILEIRA DE RADIOLOGY, 2019).

3.2 QUANTITATIVE BONE ULTRASOUND (UOQ)

Quantitative bone ultrasonography (UOQ) is a method that evaluates bone from the interaction of high-frequency sound waves with its internal structure, allowing the inference of mechanical and microstructural properties of bone tissue instead of measuring only mineral density in g/cm², as occurs in DEXA. Frequently, the equipment used in the UOQ is dedicated, as in figure 5, where a model that performs the examination in the proximal phalanx is presented (MOAYYERI et al., 2015).

Figure 5

Quantitative bone ultrasonography (QU) equipment of the phalanx, used in the evaluation of primary and secondary osteoporosis



Source: HAMIDI et al. (2022).

It is a technique free of ionizing radiation, portable, and relatively inexpensive, which facilitates its use in osteoporosis screening programs in large populations, in primary care services, and in regions with limited infrastructure for conventional bone densitometry exams (MOAYYERI et al., 2015). Under these conditions, the calcaneus is the preferred site of evaluation because it is composed mostly of trabecular bone, which is highly metabolic and undergoes early changes due to the imbalance between bone resorption and formation characteristic of osteoporosis (MOAYYERI et al., 2015).

The choice of calcaneus, in addition to reflecting its high proportion of trabecular bone, is also related to the easy positioning of the patient and the lower interference of thick soft tissues, which contributes to greater reproducibility of the results in screening scenarios. Figure 6 shows a UOQ equipment dedicated to performing calcaneal examination. (ALMANSOUR et al., 2021).

Figure 6

Quantitative bone ultrasonography (UOQ) equipment for calcaneal evaluation (SONOST-2000 model)

Source: GE Healthcare (2023).

From a clinical perspective, UOQ stands out for combining operational practicality and the provision of functional information about the skeleton, going beyond the simple quantification of bone density. Because it is a fast, portable, low-cost exam free of ionizing radiation, it can be performed in offices, basic health units, outpatient clinics and even in screening campaigns, facilitating access for elderly patients, patients with reduced mobility or residents in regions without DEXA densitometry available. By evaluating parameters related to stiffness and trabecular microarchitecture, UOQ allows the early identification of individuals with probable bone quality impairment, directing them to complementary investigation and preventive interventions, which reinforces its role as a screening tool in populations at risk for osteoporosis and fragility fractures (ALMANSOUR et al., 2021).

The test is quick, does not require complex preparation, and can be performed at the bedside or in basic health units, favoring access for elderly populations or those with reduced

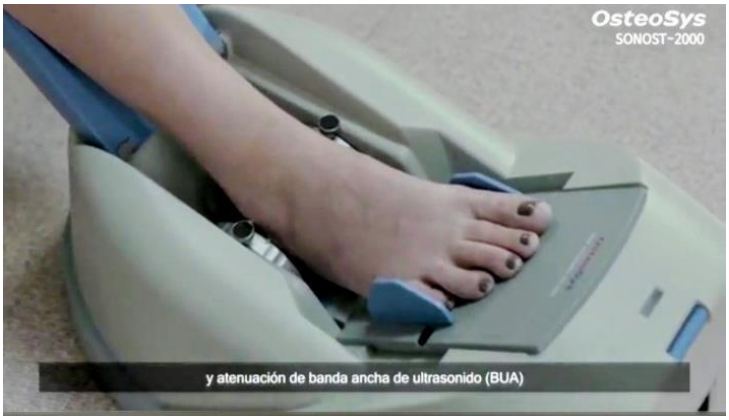
mobility, who often encounter logistical barriers to perform DEXA (ALMANSOUR et al., 2021).

3.2.1 How Quantitative Bone Ultrasound Works

From the physical point of view, the operating principle of UOQ is based on the emission of mechanical waves by an emitting transducer and its detection by a receiving transducer, positioned on opposite sides of the bone segment analyzed, as we can see in figure 7 where the patient's heel is accommodated in the equipment in such a way as to ensure the correct positioning mentioned above, Normally, a coupler medium is used to reduce energy losses at the skin-transducer interface. In this arrangement, the emitting transducer converts electrical energy into high-frequency mechanical vibrations, which propagate through the soft tissues and bone, while the receiver converts these vibrations back into electrical signals, allowing the equipment to record how the wave was modified as it passed through the bone tissue. The use of a coupling medium, usually a specific gel, minimizes the reflection of waves on the skin surface and ensures better transmission of acoustic energy, increasing the sensitivity of the system to detect subtle variations in bone density, elasticity, and trabecular microarchitecture (NOGAARD et al., 2020).

Figure 7

Evaluation of the calcaneus by quantitative bone ultrasonography (UOQ)



Source: GE Healthcare (2023).

As the sound wave passes through the bone, its propagation ceases to be uniform and begins to reflect the physical properties of that skeletal segment. In regions with higher mineral density and greater rigidity, the trabecular structure offers greater mechanical resistance, causing the wave to travel through the tissue more quickly, while in areas with trabecular rarefaction, increased porosity and lower connectivity, the speed of propagation decreases. In addition, the complexity of trabecular microarchitecture causes multiple

reflections, dispersions, and absorptions of acoustic energy, which translates into a different degree of signal intensity loss along the way. From these modifications, the equipment is able to calculate quantitative parameters, such as the speed of sound (SOS), which expresses how fast the wave passes through the bone, and the broadband attenuation (BUA), which represents how much of the wave's energy is attenuated in a range of frequencies, both directly related to the structural and mechanical quality of the bone tissue (NOGAARD et al., 2020).

SOS represents the speed at which the sound wave travels through the bone and is directly related to structural stiffness and density: the greater the trabecular stiffness and compaction, the greater the speed of propagation; significant reductions in this value suggest loss of trabecular continuity, increased porosity and, consequently, less capacity to withstand mechanical loads (CAROLAN et al., 2020).

The BUA evaluates the degree of attenuation of the wave when it crosses the bone in a frequency spectrum, reflecting the way the trabecular microarchitecture disperses and absorbs acoustic energy; reduced BUA values tend to indicate trabecular rarefaction, decreased connectivity, and greater bone fragility, while preserved values suggest relatively intact microstructure (CAROLAN et al., 2020).

More modern systems combine the basic sonographic parameters in derived indices, seeking to translate into a single number the complex interaction between density, stiffness and integrity of the bone microarchitecture. In this approach, SOS and BUA values are weighted by specific formulas for each equipment, resulting in composite scores such as the *Quantitative Ultrasound Index* (QUI). This index works as a "summary" of the acoustic information obtained: the higher the CHI, the better the bone's ability to conduct and attenuate the sound wave in a way that is compatible with a dense, organized and resistant structure; Reduced values, in turn, suggest loss of trabecular connectivity, increased porosity, and greater mechanical fragility. In this way, the QUI facilitates the clinical interpretation of the data, allowing the patient to be quickly classified into risk ranges and to compare results between serial evaluations of the same individual, although it remains dependent on the protocol and manufacturer used (NOGAARD et al., 2020). A detailed analysis of these parameters is key to understanding what UOQ is actually measuring in terms of skeletal integrity (CAROLAN et al., 2020).

3.2.2 UOQ-generated diagnostics

In the diagnostic context, the values of SOS, BUA and composite indices, such as CHI, are not interpreted in isolation, but are compared to reference databases incorporated

into the equipment itself. These databases bring together measurements obtained from healthy populations and are organized according to variables such as gender, age group, and, in some cases, ethnicity, in order to reflect expected physiological differences between different groups. The interface of the Osteosys equipment software, which contains information obtained after examining a calcaneus, can be seen in figure 8. From the comparison of the SOS and BUA values taking into account the variables, the system calculates relative scores that express how many standard deviations the patient's result deviates from the mean of the reference group, constructing values analogous to the T-score used in DEXA densitometry. This standardization allows for classifying bone quality into ranges of normality or increased risk for fractures, in addition to enabling longitudinal follow-up, comparing serial examinations of the same individual over time (LI et al., 2022).

Figure 8

Software interface of the SONOST-2000 quantitative bone ultrasonography (UOQ) equipment

Source: GE Healthcare (2023).

Although the UOQ does not directly provide bone mineral density in g/cm², studies have shown that reductions in ultrasound parameters are associated with a higher incidence of fractures, especially in the elderly, which validates its use as a prognostic tool for osteoporotic fracture risk (LI et al., 2022). As such, UOQ is particularly useful for identifying individuals at increased risk who would benefit from complementary DEXA work-up and preventive interventions, even if it does not replace, from a regulatory perspective, the gold standard for definitive diagnosis of osteoporosis (LI et al., 2022).

In practice, clinical interpretation is usually based on derived indices that integrate SOS, BUA, and equipment correction factors, generating a global bone quality value that can be categorized into low, moderate, or high risk ranges of frailty (GROSSMAN et al., 2021). Several studies point to significant correlations between these ultrasound indices and

the risk of hip, vertebrae, and wrist fractures, reinforcing that UOQ is a reliable option for initial risk stratification in patients who have not yet undergone densitometry (GROSSMAN et al., 2021).

However, important limitations remain, such as the dependence on the anatomical site studied, the variability between different models and equipment manufacturers, the lack of international standardization of cutoff points, and a precision inferior to that of DEXA, factors that justify its predominant use as a complementary and screening method, and not as a complete substitute for bone densitometry (GROSSMAN et al., 2021).

3.3 QUANTITATIVE COMPUTED TOMOGRAPHY (QCT)

Quantitative computed tomography (QCT) is a high-precision diagnostic method that leverages multidetector computed tomography (CT) technology to measure bone mineral density (BMD) in a truly volumetric manner, expressed in absolute units of mg/cm³, a three-dimensional metric that considers the actual volume of the bone analyzed, as opposed to integrated or projected measurements. To understand the superiority of QCT, it is essential to contrast it with dual-energy X-ray densitometry (DEXA), the current gold standard, while DEXA generates a two-dimensional areal bone mineral density (g/cm²), resulting from the overlapping of bone layers in a flat projection that does not distinguish depth or internal compartments, QCT acquires thin axial tomographic images (1-3 mm) reconstructed in *voxel-based* 3D volumes, allowing an exhaustive assessment of bone geometry and composition in any skeletal region (ENGELKE et al., 2015). Figure 9 shows a representative image of a patient being positioned on the examination table for a CT scan.

Figure 9

Illustrative image of the patient's positioning for quantitative computed tomography (QCT) examination

Source: Mindways Software Inc..

This three-dimensional approach enables precise and separate segmentation of the cortical bone, the dense and compact outer layer, which makes up about 80% of the total skeletal mass and confers primary mechanical rigidity, of the trabecular bone, or spongy bone, located inside vertebrae, proximal ends of the femur and metaphyses, characterized by a network of interconnected trabeculae that represents only 20% of the mass, but it is metabolically hyperactive, with a remodeling rate 10-20 times higher than cortical due to high vascularization and sensitivity to hormonal (estrogen, parathyroid hormone), nutritional (calcium, vitamin D) and inflammatory oscillations. Precisely because of this vulnerability, the trabecular bone suffers early losses in osteoporosis, up to 2-3% per year in postmenopausal women, manifesting trabecular thinning, increased porosity, and loss of connectivity before the cortical bone is significantly affected, which makes QCT particularly valuable for the initial detection of this subclinical bone loss, identifying risks of vertebral or femoral fracture in reversible stages, when interventions such as bisphosphonates or denosumab can still restore microarchitecture (ENGELKE et al., 2015).

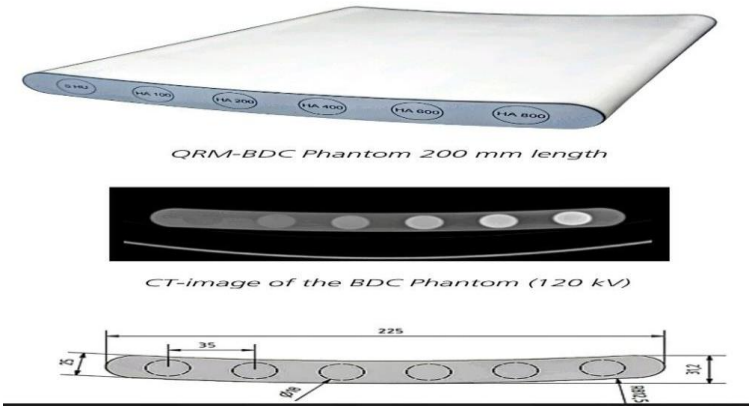
In addition to quantifying volumetric bone mineral density, QCT provides important information about bone microarchitecture, contributing to a more comprehensive understanding of bone quality. The ability to differentiate bone compartments allows the detection of structural changes that are not fully captured by two-dimensional methods. Thus, QCT has been shown to be particularly useful in metabolic studies, in the evaluation of patients with secondary bone diseases, and in clinical situations in which diagnostic accuracy is essential. (LEE; KUO, 2021).

3.3.1 How TCQ works

From a technical point of view, QCT uses a calibration *phantom* positioned simultaneously with the patient on the CT scanner table, containing materials with known bone densities that serve as absolute reference standards throughout image acquisition. Two distinct models of phantons used in QCT are shown in Figures 10 and 11. These phantons are essential for compensating for variations in the X-ray beam and ensuring consistent measurements between different pieces of equipment. During the exam, the CT scanner makes thin axial sections, usually in the lumbar spine (L1-L3) or in the hip, regions rich in trabecular bone that are more sensitive to the initial changes of osteoporosis (ENGELKE et al., 2015).

Figure 10

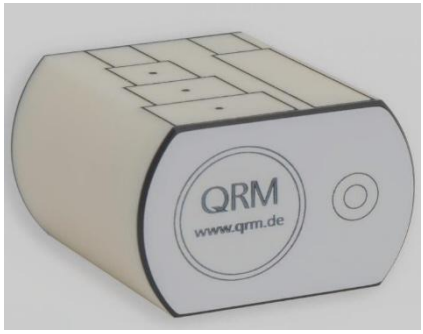
QRM-BDC calibration phantom used in Quantitative Computed Tomography (QCT)



Source: QRM GmbH.

Figure 11

Cylindrical phantom of the MRQ used for quality control and calibration in quantitative computed tomography



Source: QRM GmbH.

The specific TCQ software compares the attenuation coefficients of the bone tissues captured in the images with the known values of the phantom, converting this information into accurate volumetric bone mineral density (mg/cm³). This automated process segments pure trabecular bone, excluding soft and cortical tissues, and generates reproducible results that can be compared over time. Simultaneous calibration with the phantom is essential to ensure the diagnostic reliability and comparability of the exams, regardless of the equipment used (ENGELKE et al., 2015).

One of the main technical advantages of QCT is the significant reduction of interferences that compromise the accuracy of DEXA in daily clinical practice. Degenerative changes common in the elderly, such as facet arthrosis (which thickens the vertebral joints), osteophytes (bony protuberances along the vertebral borders), scoliosis (lateral deviation of the spine that overlaps vertebrae) and vascular calcifications of the aorta (often seen in the L4 region), project directly onto the regions evaluated in DEXA, overestimating bone mineral

density values by up to 20-30% and masking real diagnoses of osteoporosis. These two-dimensional artifacts occur because DEXA projects the entire column onto a single flat image, with no ability to separate overlapping structures (LEE et al., 2020; MCCREADIE; GOLDSTEIN, 2020).

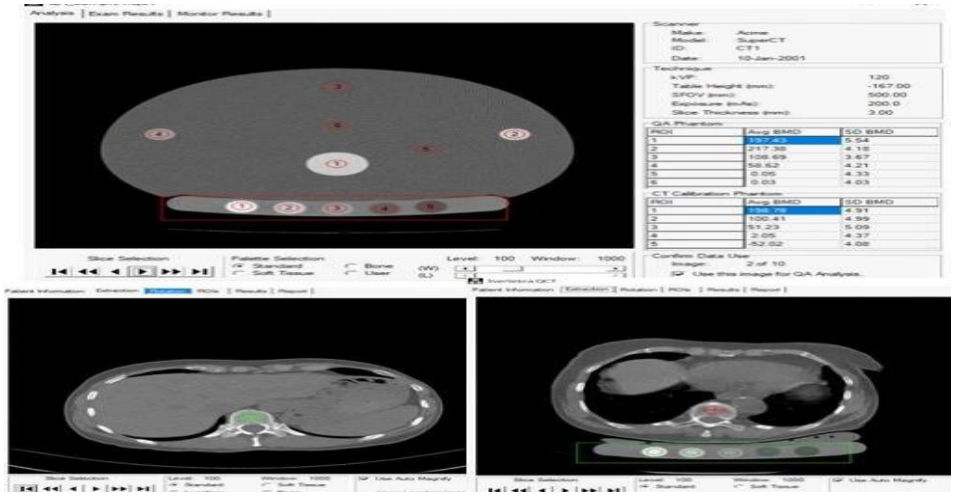
In QCT, three-dimensional acquisition with thin axial sections allows the central trabecular compartment of each vertebra to be precisely isolated, using cylindrical regions of interest (ROI) positioned in the middle of the vertebra, excluding corticalized borders and adjacent structures, eliminating these degenerative interferences and increasing diagnostic accuracy, especially in elderly patients over 65 years of age, where such alterations are prevalent. This high sensitivity makes QCT particularly effective for detecting early changes in the trabecular bone of the lumbar spine (L1-L3), which loses up to 2-3% density per year in the early stages of postmenopausal osteoporosis, allowing preventive interventions before vertebral fractures occur (LEE et al., 2020; MCCREADIE; GOLDSTEIN, 2020).

3.3.2 TCQ-generated diagnosis

The diagnosis of osteoporosis by means of QCT is based, above all, on the evaluation of the volumetric bone mineral density (BMD) of the trabecular bone, focusing on the regions richest in this type of bone, the lumbar spine (vertebrae L1 to L3) and the hip (mainly neck and trochanter femoris). These areas are chosen because trabecular bone is metabolically more active, remodels more frequently, and is one of the first to suffer loss in osteoporosis, especially in postmenopausal women and in patients with systemic diseases or long-term corticosteroid use. In QCT, BMD is expressed in mg/cm³ (or g/cm³) and obtained by means of cylindrical regions of interest (ROI) positioned in the center of the vertebra or femoral neck, ensuring a purely volumetric measurement of the trabecular compartment, free from interference from the cortical bone and adjacent structures, this information is present in figure 12, where it is possible to visualize both the calibration phantom and the ROI, represented by a red circle, present in the vertebra. (LEE et al., 2020).

Figure 12

Interface of the quantitative computed tomography (QCT) analysis software with calibration phantom



Source: Mindways Software Inc.

Volumetric BMD values are then compared with specific reference scales for QCT, usually based on databases of healthy young adults (reference standard for T-score) and on populations by age, sex, and race (Z-score). In general, in the lumbar spine, values below 80 mg/cm³ are considered compatible with osteoporosis, while values between 80 mg/cm³ and 120 mg/cm³ indicate osteopenia (low bone mass, but still above the osteoporosis threshold). This classification allows the identification of early structural changes, such as trabecular thinning and increased porosity, before significant bone loss detectable by two-dimensional methods, such as DEXA densitometry, occurs. Thus, QCT contributes to early intervention with non-pharmacological (exercise, calcium and vitamin D supplementation) or pharmacological (bisphosphonates, denosumab, teriparatide) measures, reducing the risk of vertebral and femoral fractures in high-risk patients (LEE et al., 2020).

Despite its high sensitivity and ability to provide a detailed structural assessment, QCT has important limitations that restrict its routine use in clinical practice. Chief among these is the radiation dose, which is significantly higher than that of DEXA densitometry, while a DEXA scan of the lumbar spine exposes the patient to about 10–20 µSv (microsieverts), a QCT scan of the lumbar spine can achieve between 100 and 300 µSv, i.e., approximately 5 to 15 times more radiation. To give you a comparative idea, a simple chest X-ray in PA (posteroanterior projection) corresponds to about 20–100 µSv, which means that the CT scan of the lumbar spine has a radiation dose similar to 1–3 chest X-rays, while the DEXA is closer to 0.1–0.5 chest X-ray. This difference is especially relevant in young patients, in serial

examinations (frequent monitoring), and in populations at higher risk of cumulative radiation effects (WONG et al., 2021; NIEVES et al., 2021).

In addition to the radiation dose, QCT has a higher cost than DEXA and requires specific equipment (calibrated tomograph), dedicated quantitative analysis software, and calibration phantom, which reduces its availability, especially in public health services, where resources are limited. For these reasons, QCT is most often used in scientific research contexts, clinical trials, and in specific clinical situations that require an in-depth analysis of bone microarchitecture, such as secondary bone diseases, treatment failure, or disagreement between DEXA and clinical practice. Even so, its role is fundamental as a complementary method in the evaluation of osteoporosis, especially in cases where conventional densitometry has diagnostic limitations, such as severe arthrosis, scoliosis, vascular calcifications, or early bone loss not detected by DEXA (WONG et al., 2021; NIEVES et al., 2021).

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