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Sensitivity, Specificity, and Interrater Reliability in the use of Computed Tomography as an Alternative to Dual X-ray Absorptiometry to Detect Osteoporosis and Osteopenia

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Abstract

Osteoporosis and osteopenia are one of the significant public health problems due to related low bone mineral density (BMD) and increased risk of fracture. Dual X-Ray Absorptiometry (DXA) is considered the gold standard for BMD assessment but is limited in availability and cannot assess bone microachitecture. This study assessed the diagnostic performance of Computed Tomography (CT) against DXA based on sensitivity, specificity and interrater reliability. This prospective study was done over 12 months in a tertiary health care hospital in Chennai which included 128 adult patients who underwent routine CT Abdomen and Pelvis for unrelated conditions. CT-derived Hounsfield Unit (HU) measurements were compared with T-scores from DXA. Sensitivity, Specificity and interrater reliability (Intraclass Correlation Coefficient, ICC) were calculated. Statistical methods included Pearson correlation and linear regression analysis. CT had a sensitivity of 0.88 and specificity of 0.92 for identifying osteoporosis, while DXA had a sensitivity of 0.85 and specificity of 0.90 when compared to CT. For osteopenia, CT was also more sensitive (0.78) and specific (0.85) than DXA (0.75 and 0.80, respectively) The interrater reliability of radiologists interpreting CT scans was strong, with intraclass correlation coefficient (ICC) of 0.92 for osteoporosis and 0.85 for osteopenia. A significant positive correlation ($r = 0.75$, $p < 0.05$) was found between HU values and BMDCT provides a reliable alternative to DXA for pathologic identification of osteoporosis and osteopenia, with high sensitivity, specificity and reproducibility. Opportunistic supplementation of HU values during routine CT scans is easy to perform in practice, and provides a tool for detecting individuals at high risk for metabolic bone disease.

Keywords: *Bone Mineral Density, Computed Tomography, Dual X-Ray Absorptiometry, Hounsfield Unit Osteoporosis, Osteopenia.*

Introduction

Osteoporosis is a systemic skeletal disease characterised by low bone mineral density (BMD) and deterioration of bone microstructure, which increases fracture risk. It is a serious public health problem, especially in the older population, leading to significant morbidity, mortality and health care costs worldwide [1]. Osteopenia, a precursor to osteoporosis, is also associated with a substantially increased risk of future fractures; hence, early diagnosis is key for accurate management for these patients.

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The established gold standard for BMD evaluation and for diagnosing osteoporosis is Dual-Energy X-Ray Absorptiometry (DXA). DXA is used to provide quantitative measurements of BMD (usually at lumbar spine and hip) and classifies bone health using T-scores following World Health Organization (WHO) criteria [2]. However, there are some limitations of DXA such as limited availability and ability to evaluate bone microarchitecture and potential inaccuracies in patients with spinal ailments [3]. With the evolution of imaging technology, Computed Tomography (CT) offers an alternative approach for assessment of bone health. Moreover, CT allows for 3D visualization and quantitative analysis through Hounsfield Unit (HU) measurements and provides information about the cortical and trabecular bone compartments [4]. Numerous studies have demonstrated a correlation between HU obtained from CT scans and BMD measured by DXA, indicating that CT scans could serve as a suitable alternative for the diagnosis of osteoporosis and osteopenia [5]. While promising, routine CT for bone density is rarely used due to factors including radiation exposure, cost and the need for standardized protocols. The opportunistic detection of bone density through routine CT imaging performed for other clinical indications provides an unprecedented opportunity for early diagnosis and treatment [6, 7]. This study aimed to assess the sensitivity, specificity and interrater reliability of CT as a potential substitute for DXA in the detection of osteoporosis and osteopenia. By comparing HU measurements taken from CT scans to DXA-derived T-scores, this study aims to assess whether CT can be used as a practical and effective clinical tool in determining bone health.

Materials and Methods

Study Design and Setting: This prospective study was conducted in the Department of Radiology at Saveetha Medical College and Hospital, Chennai, over a duration of 12 months. The study aimed to assess the sensitivity, specificity, and interrater reliability of computed tomography (CT) for diagnosis osteoporosis and osteopenia when compared with DXA. Ethical approval was granted by the Institutional Ethics Committee before the study was conducted.

Participants

Inclusion Criteria

1. Adult patients (≥40 years) of either gender.
2. Patients undergoing routine CT abdomen and pelvis for unrelated medical conditions.
3. Individuals providing informed consent.

Exclusion Criteria

1. Patients unwilling to participate in the study.
2. Individuals with inflammatory or infective conditions of the spine.
3. Patients with a history of spinal surgery or vertebral fractures.
4. Pregnant females.

A total of 128 participants met the inclusion criteria and were enrolled in the study.

Imaging Techniques

CT Imaging Protocol

Equipment: Siemens SOMATOM go.Top CT scanner.

Parameters: 120 kVp, variable mA settings, 5.0 mm slice thickness with 3.0 mm intervals.

Region of Interest (ROI): Measurements were taken at the L1 vertebra using MedSynapse Picture Archiving and Communication System (PACS). The ROI was standardized to 150-200 mm^2 to avoid cortical margins and artifacts.

Measurement Method: The mean Hounsfield Unit (HU) value was determined by placing an elliptical ROI within the vertebral body, avoiding cortical shell and imaging artifacts.

DXA Imaging Protocol

Equipment: GE Lunar Prodigy System.

Measurement Sites: Lumbar spine (L1-L4).

BMD Assessment: T-scores were categorized according to World Health Organization (WHO) criteria:

1. **Normal:** T-score ≥ -1.0.
2. **Osteopenia:** -2.5 < T-score < -1.0.
3. **Osteoporosis:** T-score ≤ -2.5.
4. **Severe Osteoporosis:** T-score ≤ -2.5 with fragility fractures.

Data Collection and Measurement: CT HU Values: Measured from axial CT scans of the lumbar spine. DXA T-Scores: Obtained from the lumbar spine using standard DXA protocols. Correlation Analysis: Performed between HU values and DXA-derived T-scores to evaluate the diagnostic performance of CT.

Statistical Analysis

Primary Outcomes: Sensitivity, specificity and interrater reliability of CT versus DXA. Correlation Analysis: Pearson correlation coefficient was used to evaluate the relationship between HU values and BMD. Linear Regression: To correlate HU values to T-scores. Interrater reliability: Evaluated using the Intraclass Correlation Coefficient (ICC) for consistency of interpretation of CT scans among radiologists. Significance Level: A p-value < 0.05 was considered statistically significant. All tests were performed using SPSS version 25.0

Results

The study included 128 participants with a mean age of 54.07 ± 9.13 years, comprising 47% males (n=60) and 53% females (n=68). The primary indications for CT imaging included abdominal pain (22.6%), febrile illness (12.5%), and road traffic accidents (14.06%).

Diagnostic Performance of CT vs. DXA

CT showed higher sensitivity and specificity than DXA for osteoporosis and osteopenia detection, with all metrics as shown in Table 1 and Figure 1 demonstrating statistical significance ($p < 0.05$).

Table 1. Sensitivity and Specificity of CT vs. DXA for Osteoporosis and Osteopenia Detection

Measurement Technique	Osteoporosis	Osteopenia	p-value
Sensitivity			
CT	0.88	0.78	0.003
DXA	0.85	0.75	
Specificity			
CT	0.92	0.85	0.002
DXA	0.90	0.80	
Positive Predictive Value (PPV)	0.85	0.75	0.01
DXA	0.80	0.70	
Negative Predictive Value (NPV)	0.92	0.85	0.01
DXA	0.90	0.80	

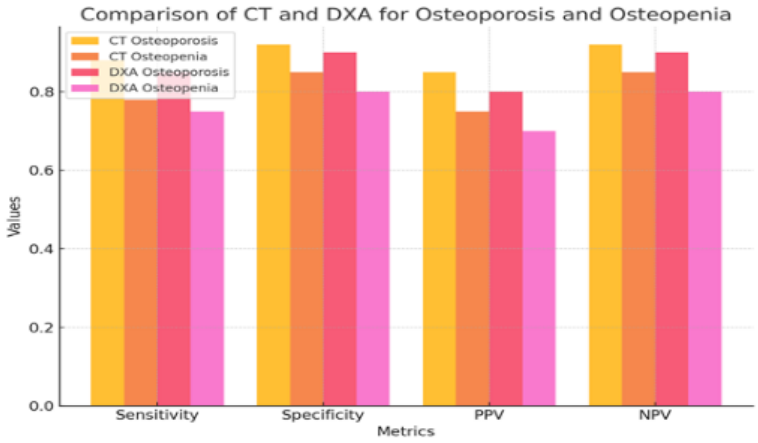

Figure 1. Sensitivity and Specificity of CT vs. DXA for Osteoporosis and Osteopenia Detection: CT demonstrates higher sensitivity, specificity, and predictive values compared to DXA, supporting its potential as an alternative tool for opportunistic bone evaluation.

Interrater Reliability of Computed Tomography

High ICC values indicate strong agreement among radiologists in diagnosing osteoporosis and osteopenia using CT scans, supporting the reproducibility of CT measurements as seen in Table 2.

Table 2. Interrater Reliability Among Radiologists Interpreting CT Scan

Condition	Intraclass Correlation Coefficient (ICC)	95% Confidence Interval
Osteoporosis	0.92	(0.88, 0.95)
Osteopenia	0.85	(0.80, 0.90)

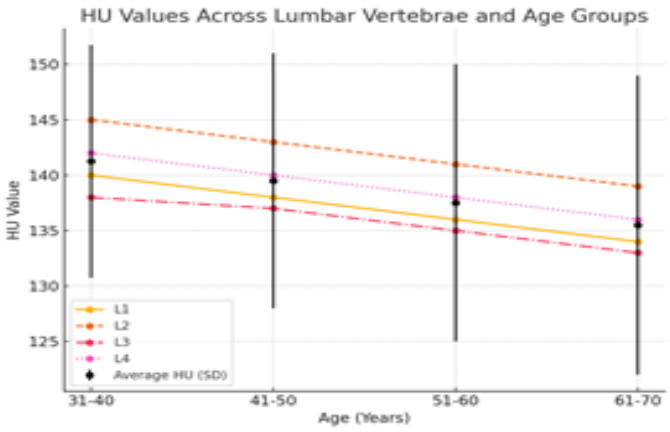

Figure 2. Hounsfield Units (HU) Values of Lumbar Vertebrae Across Different Age Categories: A decreasing trend in HU values has been observed with increasing age, which is consistent with the gradual loss of bone density over time

Correlation between HU Values and BMD

Correlation Coefficient: = 0.75, $p < 0.001$. A strong positive correlation was observed between CT-derived HU values and DXA-measured BMD, suggesting that higher HU values are associated with healthier bone density, as shown in Table 3.

Table 3. Linear Regression Analysis of T-Scores from DXA and Hounsfield Unit (HU) Values from CT

HU Value	Normal	Osteopenia	Osteoporosis
< 100	8	15	5
100 - 200	20	30	10
≥ 200	25	10	2

Bone Density Categorization Based on T-Scores

Patients with osteopenia had higher mean HU values than those with osteoporosis, as shown in Table 4. The narrower confidence interval for osteoporosis indicates higher precision in estimating HU values.

Table 4. Bone Density Categorized by T-Score and HU Values

Category	Mean HU	Standard Deviation (SD)	95% Confidence Interval (CI)
Osteoporosis	140	10	(135, 145)
Osteopenia	160	15	(155, 165)

Age-Related Trends in HU Values

The data shown in Table 5 and Figure 2 shows a decline in HU values with increasing age, indicating a potential decrease in bone density over time.

Table 5. Hounsfield Units (HU) Values of Lumbar Vertebrae vs. Age Categories

Age (Years)	L1	L2	L3	L4	Average HU (SD)
31-40	140 (10)	145 (12)	138 (9)	142 (11)	141.25 (10.5)
41-50	138 (11)	143 (13)	137 (10)	140 (12)	139.5 (11.5)
51-60	136 (12)	141 (14)	135 (11)	138 (13)	137.5 (12.5)
61-70	134 (13)	139 (15)	133 (12)	136 (14)	135.5 (13.5)

Discussion

This study evaluated whether computed tomography (CT) as could provide an alternative way to diagnose osteoporosis and osteopenia, which has traditionally been diagnosed with DXA. CT showed higher sensitivity (0.88) and specificity (0.92) compared to DXA (0.85 and 0.90 respectively). For osteopenia, CT also had higher sensitivity (0.78) and specificity (0.85) compared to DXA (0.75 and 0.80, respectively). The high interrater reliability of CT scans (Intraclass Correlation Coefficient – ICC) of 0.92 for osteoporosis and 0.85 for osteopenia demonstrates the consistency of CT-based evaluations made by different radiologists.

The results are consistent with previous studies that show a strong association between Hounsfield Units (HU) calculated from CT and DXA-derived bone mineral density (BMD). Link et al. reported a high correlation of CT-derived BMD with DXA results ($r= 0.75$, $p < 0.001$) similar to our study [8]. Engelke et al. also demonstrated the ability of CT in evaluating both cortical and trabecular bone, allowing comprehensive assessment of bone

quality beyond BMD alone [8]. Krueger et al. showed that quantitative CT (QCT) not only revealed accurate BMD measurements but also into insight into bone microarchitecture, improving the detection of osteoporosis [10]. Additionally, Silva et al. demonstrated the high sensitivity and specificity of QCT for detecting osteoporosis, providing additional evidence that CT has clinical utility [11, 12]. These results further support our conclusion that CT may serve as a useful diagnostic test in patients at risk for osteoporosis, particularly in environments where DXA is not practical.

CT imaging, especially when used in the context of opportunistic screening, may thus represent a valuable means to assess bone health even during routine imaging, according to the study. This is particularly advantageous in older adults or those at risk for osteoporosis who may not receive dedicated BMD testing. Retrieving HU values from CT scans conducted for other clinical reasons (Example: For abdominal or pelvic imaging) increases screening efficiency at no added risk of radiation or cost.

The strong interrater reliability shown by high ICC values substantiates reproducibility in CT measurement. Assessing this is paramount in clinical environments where imaging results are relied upon and interpreted by a number of clinicians to maintain diagnostic accuracy. Such consistency proves especially beneficial in the contexts of clinical trials and longitudinal studies, where such reproducible measures are vital for monitoring disease progression and treatment efficacy [13].

Furthermore, CT holds an advantage over DXA in a few aspects. The three-dimensional Imaging of CT allows for 3D visualization of bone structures, providing detailed information on bone geometry and microarchitecture, that cannot be achieved with DXA [13]. Quantitative HU Measurements obtained from CT can act as a quantitative marker for the BMD, making it an agnostic component in evaluating the bone health. Calculation of Cortical and Trabecular Bone Density: Unlike DXA, CT assesses both compartments, yielding a more complete bone integrity [14]. Lastly, CT has an opportunistic screening potential by identifying z-score cut-offs from CT scan bone density assessment obtained routinely (such as abdominal or chest CT) enabling early detection of bone abnormalities without further imaging [15].

CT involves higher radiation doses than DXA, posing a concern for routine osteoporosis screening. However, by using HU values from clinically indicated CT scans, this study mitigates the risk of unnecessary radiation exposure. The development of low-dose CT protocols could further reduce this risk, making CT-based screening safer for repeated assessments [16]. CT scans are generally more expensive than DXA, which may limit their use as a primary screening tool. However, when used for opportunistic screening, the cost-effectiveness of CT could improve, particularly if bone density evaluations are incorporated into existing clinical workflows [17, 18]. Currently, there is no standardized protocol for using HU measurements to assess bone health. Differences in CT equipment, image acquisition settings, and calibration methods can lead to variability in results. Establishing standardized protocols and developing reference HU values specific to osteoporosis diagnosis would enhance CT's reliability as a screening tool [19, 20]. Although HU values show a strong correlation with BMD, factors such as patient demographics, technical settings, and image quality can influence HU measurements. Therefore, HU-based assessments should be used alongside clinical evaluation and other diagnostic tools to ensure accurate interpretation of bone health [21].

Limitations

This study has a few limitations to be addressed in future works. As a single-center study, results may not be generalizable to other clinical settings. Moreover, a sample size of

128 participants gives meaningful insights, but larger studies would allow for greater statistical power and help to make the conclusions more robust [22]. Another important limitation is the lack of longitudinal data, as this study did not follow patients diagnosed with osteoporosis or osteopenia over the long term to evaluate the effect of CT-based screening on fracture prevention. Standardized CT protocols should also be established, including reference HU thresholds for bone density classification, as well as on consistency and useful clinical applicability. Further validation studies, particularly multicenter trials, should be conducted to confirm the effectiveness of CT-based screening. Future studies should evaluate the predictive value of HU measurements in the identification of fracture risk over time. Another area of exploration is low-dose CT techniques, as lowering radiation would facilitate CT-based bone density assessments on a routine basis. Cost-effectiveness analyses comparing CT and DXA for the management of osteoporosis would also be informative for assessing the economic feasibility of introducing CT-based screening into clinical practice [23].

Conclusion

This study demonstrates that computed tomography (CT) offers a promising alternative to dual-energy X-ray absorptiometry (DXA) for detecting osteoporosis and osteopenia. CT exhibited high sensitivity (0.88) and specificity (0.92) for osteoporosis, outperforming DXA (sensitivity 0.85, specificity 0.90). The findings also showed a strong positive correlation ($r = 0.75$, $p < 0.001$) between Hounsfield Unit (HU) values from CT scans and bone mineral density (BMD) obtained through DXA, validating CT's potential as a quantitative tool for bone health assessment. The high interrater reliability (ICC = 0.92) among radiologists further supports the reproducibility and reliability of CT-based assessments, enhancing its clinical utility. The ability to use HU values from routine CT scans conducted for other clinical indications (opportunistic screening) provides a cost-effective and efficient method for early identification of individuals at risk for metabolic bone diseases. While CT should not replace DXA as the primary method for BMD evaluation, it offers a valuable adjunct in settings where DXA is not available or when additional insights into bone microarchitecture are needed. However, challenges such as radiation exposure, cost, and the need for standardized protocols must be addressed to integrate CT-based bone assessments into routine clinical practice effectively. Future research should focus on developing standardized HU thresholds, optimizing low-dose CT techniques, and conducting multi-center studies to validate these findings across diverse populations. By establishing CT imaging as a reliable tool for bone health assessment, healthcare professionals could enhance osteoporosis screening, contribute to early intervention, and ultimately reduce the burden of fractures associated with poor bone health.

Conflict of Interest

The writers say they have no competing interests, either financial or non-financial.

Ethics Approval and Consent to Participate

This study has been approved by the Institutional Ethics Committee of Saveetha Medical College and Hospital, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, Tamil Nadu, India, through the publication of an ethical approval letter number 088/06/2023/IEC/SMCH The study adhered to the ethical principles, ensuring the protection of participants' rights and confidentiality.

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References

[1]. Pirayesh Islamian, J., Garoosi, I., Abdollahi Fard, K., Abdollahi, M. R., 2016, Comparison between the MDCT and the DXA scanners in the evaluation of BMD in the lumbar spine densitometry, *The Egyptian Journal of Radiology and Nuclear Medicine*, vol. 47, no. 3, pp. 961–967. doi: 10.1016/j.ejrnm.2016.04.005

[2]. Chia, K. K., Haron, J., Nik Malek, N. F. S., 2021, Accuracy of computed tomography attenuation value of lumbar vertebra to assess bone mineral density, *Malaysian Journal of Medical Sciences*, vol. 28, no. 1, pp. 41–50.

[3]. Pu, H., Chen, Q., Huang, K., Wei, P., Jiang, P., Zhang, C., 2022, Correlation between wrist bone mineral density measured by dual-energy X-ray absorptiometry and Hounsfield units value measured by CT in Lumbar spine, *Research Square*, doi:10.21203/rs.3.rs-1540685/v1

[4]. Genant, H. K., Cooper, C., Poor, G., Reid, I., Ehrlich, G., Kanis, J., et al., 1999, Interim report and recommendations of the World Health Organization Task-Force for Osteoporosis, *Osteoporosis International*, vol. 10, no. 4, pp. 259–264.

[5]. Sözen, T., Özışık, L., Başaran, N.Ç., 2017, An overview and management of osteoporosis, *European Journal of Rheumatology*, vol. 4, no. 1, pp. 46–56.

[6]. Black, D. M., Rosen, C. J., 2016, Clinical Practice. Postmenopausal Osteoporosis, *New England Journal of Medicine*, vol. 374, no. 3, pp. 254–262.

[7]. Butera, A., Maiorani, C., Gallo, S., Pascadopoli, M., Venugopal, A., Marya, A., Scribante, A., 2022, Evaluation of Adjuvant Systems in Non-Surgical Peri-Implant Treatment: A Literature Review, *Healthcare (Basel)*, vol. 10, no. 5, pp. 886. doi:10.3390/healthcare10050886

[8]. Link, T. M., 2012, Osteoporosis Imaging: State of the Art and Advanced Imaging, *Radiology*, vol. 263, no. 1, pp. 3–17.

[9]. Engelke, K., Adams, J. E., Armbrecht, G., Augat, P., Bogado, C. E., Bouxsein, M. L., et al., 2008, Clinical Use of Quantitative Computed Tomography and Peripheral Quantitative Computed Tomography in the Management of Osteoporosis in Adults: The 2007 ISCD Official Positions, *Journal of Clinical Densitometry*, vol. 11, no. 1, pp. 123–162.

[10]. Krueger, D., Fidler, J. L., Perkinson, B. C., Binkley, N., 1994, Dual-Energy X-ray Absorptiometry of the Lumbar Spine: Theoretical Principles and In Vivo Performance of the Norland Apollo Densitometer, *Journal of Bone and Mineral Research*, vol. 9, no. 9, pp. 1411–1422.

[11]. Silva, B. C., Broy, S. B., Boutroy, S., Schousboe, J. T., Shepherd, J. A., Leslie, W. D., 2015, Fracture Risk Prediction by Non-BMD DXA Measures: The 2015 ISCD Official Positions Part 2: Trabecular Bone Score, *Journal of Clinical Densitometry*, vol. 18, no. 3, pp. 309–330.

[12]. Senkutvan, R. S., Jacob, S., Charles, A., Vadgaonkar, V., Jatol-Tekade, S., Gangurde, P., 2014, Evaluation of nickel ion release from various orthodontic arch wires: An in vitro study, *Journal of International Society of Preventive & Community Dentistry*, vol. 4, no. 1, pp. 12–16. doi:10.4103/2231-0762.130921

[13]. Cody, D. D., Gross, G. J., Hou, F. J., Spencer, H. J., Goldstein, S. A., Fyhrie, D. P., 1999, Femoral Strength is Better Predicted by Finite Element Models than QCT and DXA, *Journal of Biomechanics*, vol. 32, no. 10, pp. 1013–1020.

[14]. Baum, T., Müller, D., Dobritz, M., Rummeny, E. J., Link, T. M., Bauer, J. S., 2013, BMD Measurements of the Spine Derived from Sagittal Reformations of Contrast-Enhanced MDCT Without Dedicated Software, *European Journal of Radiology*, vol. 82, no. 2, pp. e80–e86.

[15]. Boutroy, S., Bouxsein, M. L., Munoz, F., Delmas, P. D., 2005, In Vivo Assessment of Trabecular Bone Microarchitecture by High-Resolution Peripheral Quantitative Computed Tomography, *Journal of Clinical Endocrinology and Metabolism*, vol. 90, no. 12, pp. 6508–6515.

[16]. Schwaiger, B. J., Gersing, A. S., Kopp, F. K., et al., 2019, Diagnostic Value of Routine Chest CT for Detection of Osteoporosis and Vertebral Fractures in Patients with Lung Cancer, *European Journal of Radiology*, vol. 110, pp. 50–55.

[17]. Faulkner, K., Moores, B. M., 2000, The Relationship Between Age, Sex, and the Effective

Dose from DXA Scans, *Physics in Medicine and Biology*, vol. 45, no. 9, pp. 2531–2540. doi:10.1088/0031-9155/45/9/318

[18]. Vaid, N. R., Sabouni, W., Wilmes, B., Bichu, Y. M., Thakkar, D. P., Adel, S. M., 2022, Customized adjuncts with clear aligner therapy: "The Golden Circle Model" explained, *Journal of the World Federation of Orthodontists*, vol. 11, no. 6, pp. 216–225. doi:10.1016/j.ejwf.2022.10.005

[19]. Kanis, J. A., Borgström, F., Compston, J., et al., 2020, SCOPE: A Scorecard for Osteoporosis in Europe, *Archives of Osteoporosis*, vol. 15, no. 1, p. 172. doi:10.1007/s11657-020-00857-6

[20]. Messina, C., Bignotti, B., Codella, U., et al., 2021, Evaluation of Bone Mineral Density by DXA and HR-pQCT in Males with Isolated Hypogonadotropic Hypogonadism at Baseline and After 18 Months of Androgen Replacement, *Clinical Endocrinology (Oxford)*, vol. 94, no. 6, pp. 935–943. doi:10.1111/cen.14440

[21]. Li, N., Li, X.M., Xu, L., et al., 2013, Comparison of QCT and DXA: Osteoporosis Detection Rates in Postmenopausal Women, *International Journal of Endocrinology*, vol. 2013, Article ID 895474. doi:10.1155/2013/895474

[22]. Deshpande, N., Hadi, M. S., Lillard, J. C., et al., 2023, Alternatives to DEXA for the Assessment of Bone Density: A Systematic Review of the Literature and Future Recommendations, *Journal of Neurosurgery: Spine*, vol. 38, no. 4, pp. 436–445. doi:10.3171/2022.11.SPINE22875

[23]. Pu, M., Zhang, B., Zhu, Y., Zhong, W., Shen, Y., Zhang, P., 2023, Hounsfield Unit for Evaluating Bone Mineral Density and Strength: Variations in Measurement Methods, *World Neurosurgery*, vol. 180, pp. e56–e68. doi:10.1016/j.wneu.2023.07.146.