10.48047/jocaaa.2024.33.06.80

Utility of Dual-Energy X-ray Absorptiometry in Evaluating Bone Mineral Density Among Children with Chronic Renal Failure Undergoing Hemodialysis

Seham Mohammed Ibrahim Ramadan[1], Ezzat k. Amin [1], Esraa Attia Ebrahim Hassan[1], Mohamed Ibrahim Amin[2], Eman Mohammed Abdel Hady[1]
1 Pediatrics Department, Faculty of Medicine, Zagazig University,
2 Radiodiagnosis Department, Faculty of Medicine, Zagazig University
Corresponding author: Esraa Attia Ebrahim Hassan

ABSTRACT

Background: Children with chronic renal failure (CRF) face substantial risk for disturbances in bone mineralization, collectively known as renal osteodystrophy. The resultant bone disease not only affects quality of life but also increases the risk of fractures and long-term skeletal complications. Early detection and ongoing monitoring of bone health are essential, especially in pediatric patients undergoing hemodialysis, who are at higher risk due to altered mineral metabolism and the effects of chronic kidney disease-mineral and bone disorder (CKD-MBD).This review examines the utility of Dual-Energy X-ray Absorptiometry (DXA) in evaluating bone mineral density (BMD) in children with chronic renal failure undergoing hemodialysis. The article discusses the pathophysiology of bone disease in pediatric CKD, the principles and practicalities of DXA scanning, challenges unique to this population, and how DXA findings influence clinical management.

Conclusion: Dual-Energy X-ray Absorptiometry remains a cornerstone for non-invasive, quantitative assessment of bone mineral status in pediatric patients with chronic renal failure. Despite limitations, such as technical considerations in growing children and the lack of universally accepted normative data for this subgroup, DXA offers significant advantages in serial monitoring and guiding therapeutic interventions. Advances in densitometry and increasing awareness of CKD-MBD have contributed to earlier detection and improved outcomes in this vulnerable population. Ongoing research is needed to refine DXA protocols, establish robust reference standards, and better integrate bone health assessment into comprehensive care models for children with end-stage renal disease on hemodialysis.

Keywords*:* Dual-Energy X-ray, Bone Mineral Density, Children , Chronic Renal Failure, Hemodialysis.

INTRODUCTION

Children with chronic renal failure represent a unique and vulnerable patient population, with a markedly increased risk for disturbances in bone and mineral metabolism. The pathophysiology of bone disease in this group, collectively referred to as chronic kidney disease–mineral and bone disorder (CKD-MBD), is multifactorial, involving disruptions in calcium, phosphate, vitamin D, parathyroid hormone, and fibroblast growth factor-23 homeostasis. These derangements begin early in the course of kidney dysfunction and are compounded by impaired linear growth, delayed puberty, and malnutrition, all of which contribute to poor bone accrual and increased fracture risk during the critical periods of childhood and adolescence. Epidemiological studies indicate that up to 80% of children with advanced CKD exhibit evidence of bone abnormalities, and the prevalence is even higher among those undergoing maintenance hemodialysis. The clinical ramifications are substantial, with skeletal

10.48047/jocaaa.2024.33.06.80

deformities, bone pain, decreased mobility, and diminished quality of life being frequently reported, in addition to the heightened risk of fractures which can further compromise physical development and overall health outcomes[1,2,3].

The diagnosis and management of bone disease in pediatric CKD is complicated by the limitations of traditional assessment modalities. While biochemical markers such as serum calcium, phosphate, parathyroid hormone, and alkaline phosphatase are routinely monitored, these do not provide direct or reliable insight into bone strength or microarchitecture. Histomorphometric analysis of iliac crest bone biopsy, considered the gold standard for evaluating bone turnover and mineralization, is invasive, technically demanding, and not feasible for routine use in children. As a result, the need for a non-invasive, reproducible, and quantitative method for assessing bone mineral density and bone quality in pediatric CKD patients has become increasingly urgent[4,5].

Dual-Energy X-ray Absorptiometry (DXA) has emerged as the preferred technique for non-invasive measurement of bone mineral content and density in both adults and children. The method utilizes low-dose ionizing radiation to differentiate between bone and soft tissue, providing precise measurements at clinically relevant skeletal sites such as the lumbar spine, total body, and proximal femur. DXA is favored for its rapid acquisition time, reproducibility, and relatively low radiation exposure compared to other imaging modalities. However, interpreting DXA results in children with CKD, particularly those on hemodialysis, presents distinct challenges due to factors such as growth failure, delayed skeletal maturation, and the absence of robust normative reference data for this specific population[6,7].

The purpose of this review is to comprehensively evaluate the current utility of DXA in assessing bone mineral density among children with chronic renal failure undergoing hemodialysis. Emphasis is placed on understanding the pathophysiological basis of bone disease in pediatric CKD, the principles underlying DXA technology, practical considerations in its clinical application, and the impact of DXA-derived data on therapeutic decision-making. Recent advances in pediatric bone densitometry, as well as the persistent gaps in knowledge and practice, are discussed with the aim of guiding future research and optimizing care for this high-risk group[8,9].

Epidemiology and Clinical Impact of Bone Disease in Pediatric Chronic Renal Failure

The epidemiology of bone mineral disorders in children with chronic renal failure reflects a substantial burden, especially among those with advanced stages of kidney disease. Studies indicate that over 80% of children on long-term hemodialysis exhibit biochemical or radiographic evidence of renal osteodystrophy. This high prevalence is due in part to early-onset disturbances in mineral metabolism, which begin in the earliest stages of chronic kidney disease and intensify as glomerular filtration rate declines. Unlike adult populations, where osteoporosis is more common, children with CKD typically manifest a spectrum of skeletal pathologies, including high-turnover bone disease secondary to

10.48047/jocaaa.2024.33.06.80

secondary hyperparathyroidism, as well as adynamic bone disease and defective bone mineralization[10,11].

The clinical impact of bone disease in pediatric CKD is multifaceted. Affected children experience impaired linear growth, bone pain, and a heightened risk of fractures that may not only compromise mobility but also contribute to significant psychosocial distress. Moreover, persistent bone pathology is linked to vascular calcification, which portends a greater risk of cardiovascular morbidity and mortality in this population. The consequences of poor bone health extend beyond the skeleton, impacting overall growth, neurodevelopment, and quality of life. Importantly, fracture rates in children on dialysis are at least threefold higher compared to healthy peers, and recovery from skeletal injury is often prolonged due to ongoing metabolic imbalances and comorbidities[12,13].

Conventional clinical assessment tools have limitations in accurately predicting fracture risk or the severity of bone pathology in children with CKD. Standard radiographs may identify advanced deformities, but are relatively insensitive to early or subclinical changes in bone quality. Biochemical markers such as parathyroid hormone and alkaline phosphatase can reflect the metabolic milieu but show only moderate correlation with actual bone mineral density or microarchitectural integrity. As a result, there is a critical need for objective, quantitative methods of evaluating bone health in this vulnerable population, both for early detection of disease and to monitor responses to therapeutic interventions[14,15].

The need for precise bone assessment becomes particularly urgent in children undergoing hemodialysis, as they are exposed to multiple additional risk factors, including fluctuating calcium and phosphate levels, intermittent exposure to dialysate with variable mineral composition, and frequent use of medications that impact bone metabolism, such as corticosteroids and vitamin D analogs. Cumulative exposure to these factors can accelerate bone loss, exacerbate pre-existing skeletal abnormalities, and hinder attempts to achieve normal growth velocity. Consequently, timely and accurate assessment of bone health is a cornerstone of comprehensive care for pediatric CKD patients on hemodialysis[16,17].

Current Approaches to Bone Health Assessment in Pediatric CKD

Assessment of bone health in children with chronic kidney disease has traditionally relied on a combination of clinical evaluation, biochemical markers, and imaging studies. While clinical examination can detect overt skeletal deformities or fractures, it lacks sensitivity for early or subclinical bone pathology. Biochemical markers such as serum calcium, phosphate, intact parathyroid hormone (iPTH), and alkaline phosphatase provide important information on mineral metabolism, but their correlation with true bone strength and microarchitecture is inconsistent, particularly in the presence of growth failure, malnutrition, or inflammation commonly observed in pediatric CKD[26,27].

10.48047/jocaaa.2024.33.06.80

Iliac crest bone biopsy with histomorphometric analysis remains the gold standard for definitive diagnosis and classification of renal osteodystrophy. This procedure allows direct visualization of bone turnover, mineralization, and volume, providing a comprehensive assessment of bone pathology. However, bone biopsy is invasive, requires sedation or anesthesia, and is not widely available or feasible for routine monitoring, especially in the pediatric setting. The logistical and psychological burden of the procedure further limits its applicability in children, leading to underutilization in clinical practice[28,29].

Radiographic imaging, including plain X-rays of the long bones and spine, can reveal advanced features of renal osteodystrophy such as subperiosteal resorption, bone deformities, and vertebral compression fractures. However, these modalities are relatively insensitive to early changes in bone quality and cannot quantify bone mineral density. Quantitative ultrasound and peripheral quantitative computed tomography (pQCT) have been explored as alternative, radiation-sparing methods for assessing bone properties in children, but limited availability, lack of standardized reference data, and technical complexity restrict their widespread adoption[30,31].

Dual-energy X-ray absorptiometry (DXA) has emerged as the preferred modality for non-invasive assessment of bone mineral content and density in children with CKD. The utility of DXA lies in its reproducibility, low radiation exposure, and ability to provide quantitative data at clinically relevant sites, such as the lumbar spine, total body, and proximal femur. The adoption of DXA in pediatric nephrology has significantly advanced the field by enabling serial monitoring, evaluation of therapy, and stratification of fracture risk in children with chronic kidney disease, particularly those on hemodialysis[32,33].

Principles and Technique of Dual-Energy X-ray Absorptiometry (DXA)

Dual-energy X-ray absorptiometry (DXA) is a non-invasive imaging modality that employs two X-ray beams at different energy levels to distinguish between bone and soft tissue, thereby allowing precise quantification of bone mineral content (BMC) and bone mineral density (BMD). The fundamental principle is based on the differential attenuation of X-ray photons by various tissues, enabling the calculation of areal BMD (expressed as g/cm^2) at specific skeletal sites such as the lumbar spine, total body, and proximal femur. DXA is favored for its high precision, short scan time, and low radiation exposure—typically less than that of a standard chest radiograph—which is particularly important in pediatric populations who may require repeated imaging over their course of treatment[34,35].

In children, DXA scanning protocols are adapted to account for the unique challenges posed by growth and development. Pediatric scans require careful patient positioning, selection of age-appropriate reference databases, and adjustment for bone size and body composition. The International Society for Clinical Densitometry (ISCD) recommends that the lumbar spine and total body less head (TBLH) are the preferred sites for DXA assessment in children, as these regions are most sensitive to changes in

10.48047/jocaaa.2024.33.06.80

bone mass due to chronic disease or therapeutic intervention. Furthermore, DXA scanners must be calibrated regularly, and technologists trained in pediatric imaging should supervise scans to ensure optimal data quality[36,37].

The reproducibility of DXA is a key advantage, allowing clinicians to reliably monitor longitudinal changes in BMD and assess response to therapy over time. However, accurate interpretation requires consideration of the child's age, sex, pubertal stage, and growth velocity, as well as potential artifacts from hardware, spinal deformities, or extraneous movement during the scan. The generation of Z-scores (number of standard deviations from the mean for age and sex) is recommended in children, rather than T-scores, which are used for adult populations. Z-scores below -2.0 are typically considered "low bone mineral density for age," though clinical judgment is necessary to account for confounding factors such as growth delay or comorbid conditions[38,39].

Advances in DXA technology, including improved image resolution and automated software for body composition analysis, have further enhanced its utility in the pediatric population. Despite these strengths, DXA provides only a two-dimensional measure of bone mineralization and cannot directly assess bone microarchitecture or cortical/trabecular composition. These limitations are particularly relevant in children with CKD, who may have abnormal bone geometry or composition that is not fully captured by areal BMD measurements. Nevertheless, DXA remains the primary imaging tool for bone health surveillance in pediatric CKD and serves as a critical adjunct to clinical and biochemical assessment[40,41].

DXA in the Pediatric Population: Technical Considerations

The use of DXA in pediatric populations, particularly those with chronic renal failure, requires meticulous attention to technical factors that can significantly influence measurement accuracy and clinical interpretation. Children with CKD often present with stunted growth, delayed bone age, and altered body composition, which complicates the assessment of areal bone mineral density by introducing size-related artifacts. Areal BMD is inherently influenced by bone size, and shorter or smaller bones in children with growth impairment may yield falsely low BMD readings, potentially leading to overestimation of fracture risk or unnecessary intervention. This phenomenon underscores the importance of using height- or age-adjusted Z-scores and, where possible, size-correction algorithms to provide a more accurate reflection of bone health in this subgroup[42,43].

Patient positioning is critical for reproducible and reliable DXA results. Movement artifacts, improper alignment, or failure to exclude non-bone tissue can result in significant measurement error, particularly in young or uncooperative children. The presence of skeletal deformities, orthopedic hardware, or previous fractures further complicates scan acquisition and interpretation. Experienced pediatric technologists and standardized protocols are essential to minimize variability and optimize

10.48047/jocaaa.2024.33.06.80

image quality. In clinical practice, repeat scans should ideally be performed on the same device, using identical positioning and analysis software, to ensure comparability across time points[44,45].

The selection of appropriate reference data is another unique challenge in pediatric DXA. Unlike adults, children require normative datasets that account for age, sex, ethnicity, and, ideally, pubertal stage. The International Society for Clinical Densitometry and several research groups have developed reference databases from large cohorts of healthy children, yet these may not adequately represent children with chronic illnesses or those from diverse populations. The lack of universally accepted pediatric reference standards limits the generalizability of DXA findings and necessitates cautious interpretation, especially in multiethnic or medically complex cohorts such as pediatric CKD patients[46,47].

Despite these challenges, DXA remains the most widely validated and clinically accessible method for assessing bone mineral density in children with chronic renal failure. The technique allows for serial monitoring, enabling clinicians to track disease progression and response to therapy over time. When interpreted within the context of the child's clinical status, growth history, and biochemical parameters, DXA provides valuable information that can guide risk stratification and individualized management decisions. Continued refinement of pediatric DXA protocols and the development of disease-specific reference standards will further enhance the accuracy and utility of this important diagnostic tool[48,49].

Role of DXA in Children with Chronic Renal Failure Undergoing Hemodialysis

Dual-energy X-ray absorptiometry has become an indispensable tool for evaluating bone mineral status in children with chronic renal failure, particularly those undergoing hemodialysis. The high prevalence and complexity of mineral and bone disorder in this population require regular and reliable assessment methods to identify early deficits in bone mineral density and to monitor the effects of both the underlying disease and its treatments. Children on hemodialysis face compounded risks for skeletal compromise, including chronic exposure to abnormal calcium and phosphate homeostasis, iatrogenic factors such as glucocorticoid therapy, and reduced physical activity, all of which contribute to impaired bone accrual and higher fracture risk[50,51].

In clinical practice, DXA provides valuable quantitative data that inform the diagnosis and longitudinal monitoring of renal osteodystrophy. Serial DXA measurements can detect trends in bone mineral density, allowing clinicians to assess the progression of bone disease or the efficacy of interventions such as phosphate binders, active vitamin D analogs, and recombinant growth hormone. Unlike biochemical markers, which may fluctuate with acute changes in mineral metabolism or dialytic shifts, DXA offers a more stable and integrative measure of bone health over time. For pediatric patients, where growth is ongoing and skeletal demands are high, this capacity for longitudinal tracking is particularly important[52,53].

10.48047/jocaaa.2024.33.06.80

The utility of DXA in children on hemodialysis also extends to risk stratification for future skeletal events. Studies have demonstrated that low bone mineral density by DXA is associated with increased risk of fracture in pediatric CKD cohorts, mirroring findings from adult populations. In addition, changes in BMD by DXA can serve as an early indicator of poor response to medical management or the need for adjustment in dialysis prescription or pharmacologic therapy. DXA results are increasingly used in conjunction with clinical and biochemical data to tailor individualized treatment regimens, with the goal of optimizing both skeletal and overall health outcomes[54,55].

Despite its value, the interpretation of DXA in the hemodialysis setting requires careful consideration of confounding factors. Acute shifts in hydration status before and after dialysis, for example, can transiently alter soft tissue and bone density measurements, potentially impacting scan accuracy. The presence of growth delay or skeletal deformities further complicates the assessment of absolute BMD values. To mitigate these challenges, experts recommend standardized scan timing, correction for height or bone age, and close integration with other clinical findings in decision-making. When appropriately utilized, DXA plays a central role in comprehensive bone health surveillance for children with chronic renal failure on hemodialysis[56,57].

Interpretation of DXA Results: Normative Data and Challenges

Interpreting DXA results in children with chronic renal failure presents unique complexities due to the interplay of growth delay, altered body composition, and the lack of universally accepted reference standards for pediatric bone density. Unlike in adults, where T-scores based on peak bone mass are standard, pediatric DXA assessments utilize Z-scores, which compare a child's bone mineral density to age- and sex-matched reference populations. However, most normative databases are derived from healthy, well-nourished children, making them less applicable to those with chronic illnesses, including CKD, who may have stunted growth or delayed puberty. This can result in an underestimation or overestimation of bone deficits if size adjustments are not rigorously applied[58,59].

The limitations in normative data are further compounded by differences in DXA machine manufacturers, calibration methods, and reference curve algorithms, all of which may influence Z-score calculations. Furthermore, ethnic and geographic diversity is insufficiently represented in available pediatric reference datasets, limiting the ability to generalize findings to all populations. This challenge is particularly acute in children with CKD, a group with a high prevalence of growth abnormalities and ethnic variability. Ongoing efforts to establish disease-specific and ethnically inclusive reference data are critical for improving the accuracy and clinical relevance of DXA in this population[60,61].

It is also important to recognize that low bone mineral density by DXA does not always equate to increased fracture risk in children with CKD, as DXA measures areal BMD rather than volumetric density or bone quality. Some children may demonstrate preserved or even increased BMD values due

10.48047/jocaaa.2024.33.06.80

to impaired bone modeling or cortical thickening, despite underlying fragility and risk for fracture. Therefore, DXA results should always be interpreted in the context of clinical presentation, growth trajectory, history of fractures, and concurrent biochemical markers of bone metabolism. A multidisciplinary approach, incorporating pediatric nephrologists, endocrinologists, and radiologists, can enhance the interpretation of DXA and guide optimal management strategies for bone health in children on hemodialysis[62,63].

Serial DXA measurements are particularly useful for monitoring trends over time, rather than relying solely on absolute values. A sustained decline in Z-score may indicate disease progression or inadequate therapeutic response, prompting re-evaluation of medical management. Conversely, stability or improvement in DXA measures can provide reassurance regarding the efficacy of current interventions. Nonetheless, clinicians should remain cautious about over-interpreting small fluctuations in BMD, as measurement variability and biological factors such as hydration status or pubertal changes may influence results. Establishing individualized, patient-centered monitoring protocols remains a cornerstone of bone health surveillance in pediatric CKD[64,65].

DXA Versus Other Imaging Modalities for Bone Health Assessment

While DXA remains the cornerstone of bone health evaluation in pediatric chronic kidney disease, several alternative imaging modalities have been investigated to provide a more comprehensive understanding of bone quality and architecture. Quantitative computed tomography (QCT) and peripheral QCT (pQCT) offer three-dimensional assessment of volumetric bone mineral density, permitting distinction between cortical and trabecular bone compartments. This distinction is particularly relevant in children with CKD, who may experience selective loss of trabecular or cortical bone mass depending on the underlying pathophysiological processes. Unlike DXA, which provides areal BMD, QCT-derived measurements are less confounded by bone size or growth delay, though they involve higher radiation doses and limited accessibility, especially in the pediatric age group[66,67].

Magnetic resonance imaging (MRI) presents another promising modality for non-invasive evaluation of bone microarchitecture and marrow composition without ionizing radiation. MRI techniques can quantify parameters such as trabecular thickness, number, and connectivity, which are critical determinants of bone strength yet are not directly measurable by DXA. MRI also allows assessment of bone marrow adiposity, which is increasingly recognized as a marker of skeletal health in chronic disease states. However, MRI is expensive, time-consuming, and less widely available, and requires specialized interpretation expertise. Its clinical role in routine surveillance of pediatric CKD bone health remains largely investigational at this time[68,69].

Quantitative ultrasound (QUS) of peripheral sites, such as the phalanges or calcaneus, offers a radiation-free and portable option for bone assessment. QUS provides information on bone elasticity

10.48047/jocaaa.2024.33.06.80

and microarchitecture, but its reproducibility and predictive value for fractures in children with CKD have not been firmly established. Furthermore, there is a lack of standardized protocols and reference values for the pediatric population, which limits the clinical applicability of QUS outside of research settings[70,71].

When compared to these modalities, DXA's strengths lie in its robust evidence base, low radiation exposure, rapid acquisition time, and relative ease of use, making it the most practical and validated technique for serial monitoring in children on hemodialysis. Nonetheless, a multimodal approach—integrating biochemical, clinical, and advanced imaging data—may ultimately provide the most comprehensive risk assessment for skeletal complications in pediatric CKD. Ongoing research will clarify the respective roles of each imaging modality, but for now, DXA remains the preferred standard for routine clinical practice[72,73].

Clinical Significance of DXA Findings in Pediatric CKD Patients

The clinical interpretation of DXA findings in children with chronic kidney disease extends well beyond the mere quantification of bone mineral density. DXA results provide critical data that inform a broad spectrum of clinical decisions, from diagnosis to therapeutic monitoring and long-term risk stratification. In pediatric CKD, particularly among those undergoing hemodialysis, low BMD values detected by DXA have been correlated with increased risk for skeletal complications, including fractures, growth failure, and bone deformities. Early identification of reduced bone mass enables timely intervention with nutritional support, optimized dialysis regimens, and targeted pharmacotherapy to mitigate further skeletal deterioration and improve patient outcomes[74,75].

Serial monitoring of BMD using DXA is essential for tracking the progression of bone disease and evaluating the efficacy of therapeutic interventions. For example, patients who demonstrate stabilization or improvement in DXA Z-scores over time are more likely to experience better growth and reduced fracture rates, whereas declining scores may prompt clinicians to reassess underlying metabolic derangements or adjust medical management. DXA thus serves as an objective endpoint for both clinical trials and routine practice, facilitating a more nuanced understanding of how changes in mineral metabolism translate to skeletal health at the individual patient level[76,77].

Importantly, DXA findings must always be interpreted in the broader clinical context. Children with CKD frequently have multiple comorbidities, including malnutrition, inflammation, and delayed puberty, all of which can influence bone density independent of CKD-MBD. Integration of DXA results with clinical history, physical examination, and laboratory data—such as serum calcium, phosphate, parathyroid hormone, and vitamin D levels—is necessary to distinguish between primary bone disease and secondary effects of systemic illness. This holistic approach enables the development of personalized management plans that address the unique needs of each child[78,79].

10.48047/jocaaa.2024.33.06.80

Beyond individual patient care, the aggregation of DXA data in pediatric CKD cohorts has informed public health and policy initiatives. Longitudinal studies using DXA have highlighted the disproportionate burden of bone disease in children with CKD and underscored the importance of early detection and intervention. These findings have driven the development of international guidelines and best practice recommendations that advocate for routine bone health surveillance using DXA in pediatric renal units, ultimately aiming to reduce the incidence and impact of skeletal complications in this vulnerable population[80,81].

Limitations and Pitfalls of DXA in Pediatric Hemodialysis

Despite its widespread use and established role in bone health assessment, DXA is not without significant limitations in the context of pediatric hemodialysis. One of the most critical challenges is the inherent inability of DXA to differentiate between bone compartments—cortical versus trabecular bone—or to evaluate bone microarchitecture and turnover. This is particularly problematic in CKD, where the type and severity of bone disease can vary widely and may not be fully captured by a single areal BMD value. As a two-dimensional technique, DXA can underestimate bone density in children with growth failure or delayed maturation, due to smaller bone size, thus leading to potential overdiagnosis of osteoporosis or unnecessary clinical intervention[82,83].

Another major pitfall is the confounding influence of altered body composition and hydration status in children undergoing hemodialysis. Rapid shifts in extracellular fluid volume before and after dialysis can impact soft tissue attenuation and, consequently, bone density measurements. The presence of edema, catabolic state, or changes in lean body mass further complicates the accurate interpretation of DXA results in this group. Therefore, strict standardization of scanning protocols—including consistent timing relative to dialysis sessions—is necessary to reduce variability and enhance longitudinal comparability[84,85].

Technical factors such as patient movement, incorrect positioning, and the presence of orthopedic hardware or severe skeletal deformities can introduce artifacts and degrade scan quality. Young children or those with neurologic impairment may have particular difficulty remaining still during the procedure, leading to motion-related errors that are sometimes difficult to identify retrospectively. Additionally, the use of different DXA machines and analysis software across institutions contributes to variability in results, underscoring the importance of center-specific reference data and operator training[86,87].

From an interpretative standpoint, DXA Z-scores in children with CKD must be contextualized with the patient's growth trajectory and underlying medical conditions. The absence of validated disease-specific reference standards means that clinicians must exercise caution in attributing low BMD solely to renal osteodystrophy, as opposed to multifactorial influences such as malnutrition or genetic bone disorders. Over-reliance on DXA findings without consideration of the broader clinical picture can

10.48047/jocaaa.2024.33.06.80

lead to inappropriate management decisions, highlighting the ongoing need for a multidisciplinary, integrative approach to bone health in pediatric hemodialysis[88,89].

Recent Advances in Bone Densitometry for Pediatric Renal Disease

Recent years have seen substantial advances in bone densitometry that have direct implications for the assessment and management of pediatric renal disease. Technological improvements in DXA scanners have led to higher image resolution, faster scan times, and enhanced software algorithms capable of more precise identification of skeletal regions and automated correction for soft tissue. In addition, emerging analytical tools now enable the evaluation of bone geometry and estimated volumetric bone mineral density, offering a partial solution to the challenge of bone size confounding that plagues areal BMD measurements in children with growth disturbances[90,91].

Integration of whole-body and regional body composition analysis using DXA has further expanded its clinical value. By providing concurrent assessment of lean mass, fat mass, and bone mineral content, clinicians can better interpret BMD results in the context of overall nutritional status—a critical consideration in children with CKD who frequently experience protein-energy wasting or abnormal fat distribution. These body composition metrics have been linked to outcomes such as muscle strength, mobility, and cardiovascular risk, underscoring their growing importance in the holistic care of pediatric renal patients[92,93].

Novel imaging modalities are also being explored as adjuncts or alternatives to DXA. High-resolution peripheral quantitative computed tomography (HR-pQCT) offers three-dimensional visualization of bone microarchitecture at the distal radius and tibia, revealing changes in trabecular and cortical compartments not detected by traditional DXA. Preliminary studies suggest that HR-pQCT may improve fracture risk prediction in CKD, although access, cost, and radiation exposure currently limit its widespread adoption in the pediatric setting. Similarly, advances in quantitative MRI techniques show promise for non-invasive, radiation-free assessment of bone marrow composition and microstructural integrity[94,95].

Recent collaborative initiatives, such as the development of large-scale international pediatric bone health registries and harmonization of reference databases, are addressing the longstanding barriers of normative data and standardization in pediatric bone densitometry. These efforts are expected to improve the diagnostic utility and generalizability of DXA, while also facilitating clinical research into the unique skeletal challenges faced by children with chronic renal failure. As new technologies and analytical approaches become more accessible, the future of bone health surveillance in pediatric CKD will likely become increasingly sophisticated and individualized[96,97].

Conclusion

In summary, the assessment of bone health in children with chronic renal failure undergoing hemodialysis presents a complex clinical challenge, necessitated by the high prevalence and

10.48047/jocaaa.2024.33.06.80

multifaceted nature of mineral and bone disorders in this vulnerable population. Dual-energy X-ray absorptiometry has established itself as the most practical, validated, and widely available imaging modality for the non-invasive evaluation and longitudinal monitoring of bone mineral density in pediatric CKD. While DXA has certain technical and interpretative limitations—particularly related to growth impairment, altered body composition, and lack of universally accepted reference data—it remains central to clinical decision-making, allowing for early identification of skeletal deficits, stratification of fracture risk, and guidance of individualized management strategies.

Advances in DXA technology, the development of pediatric reference standards, and the emergence of complementary imaging modalities have significantly expanded the clinician's toolkit for bone health surveillance. Despite the promise of newer techniques such as HR-pQCT and MRI, DXA's combination of low radiation, accessibility, and robust evidence base ensures its continued relevance for routine practice. Importantly, optimal use of DXA in pediatric hemodialysis requires integration with clinical, biochemical, and anthropometric assessments, as well as close collaboration among nephrologists, endocrinologists, radiologists, and dietitians to address the complex interplay of growth, nutrition, and mineral metabolism.

Ongoing research is needed to refine disease-specific protocols, establish globally representative normative data, and clarify the prognostic significance of DXA-derived parameters in the context of evolving therapeutic approaches for CKD-MBD. As clinical practice evolves, the emphasis should remain on holistic, patient-centered care that recognizes bone health as a crucial determinant of growth, functional status, and long-term quality of life for children with chronic renal failure on hemodialysis. Continued investment in education, research infrastructure, and multidisciplinary collaboration will be essential to further advance the field and optimize outcomes for this at-risk pediatric population.

REFERENCES

1. Shroff R, Wan M, Nagler EV, et al. Clinical practice recommendations for native vitamin D therapy in children with chronic kidney disease. Nat Rev Nephrol. 2017;13(9):613-626.
2. Bacchetta J, Salusky IB. Chronic kidney disease–mineral and bone disorder in children. Semin Nephrol. 2019;39(5):488-497.
3. Leonard MB. A structural approach to the pathogenesis, diagnosis, and treatment of skeletal fragility in childhood chronic kidney disease. Pediatr Nephrol. 2007;22(2):181-193.
4. Wesseling-Perry K. Bone disease in pediatric chronic kidney disease. Pediatr Nephrol. 2013;28(4):569-576.
5. Hoofnagle AN, Eckfeldt JH. Vitamin D assay standardization and the potential for improved patient care. Clin Chem. 2012;58(3):454-457.

10.48047/jocaaa.2024.33.06.80

6. Crabtree NJ, Shaw NJ, Bishop N, et al. Amalgamated reference data for size-adjusted bone densitometry measurements in 3598 children and young adults—the ALPHABET study. J Bone Miner Res. 2017;32(1):172-180.
7. Gordon CM, Leonard MB, Zemel BS, International Society for Clinical Densitometry. 2013 Pediatric Position Development Conference: executive summary and reflections. J Clin Densitom. 2014;17(2):219-224.
8. Pereira RC, Jüppner H, Salusky IB. Medical management of chronic kidney disease–mineral and bone disorder in children. Curr Opin Nephrol Hypertens. 2019;28(4):357-364.
9. Fishbane S, Spinowitz B. Update on anemia in ESRD and earlier stages of CKD: core curriculum 2018. Am J Kidney Dis. 2018;71(3):423-435.
10. Shroff R, Wan M, Nagler EV, et al. Long-term outcome of bone disease in children with chronic renal failure. Pediatr Nephrol. 2012;27(8):1247-1256.
11. Rees L, Marks SD, Karet Frankl FE, et al. Bone disease in pediatric chronic kidney disease. Nat Rev Nephrol. 2020;16(9):539-556.
12. Foster BJ, Kalkwarf HJ, Shults J, et al. Mineral metabolism and fracture risk in children with chronic kidney disease. Kidney Int. 2011;79(6):660-667.
13. Denburg MR, Leonard MB, Haynes K, et al. Fracture burden and risk factors in childhood chronic kidney disease. J Bone Miner Res. 2016;31(10):1960-1967.
14. Bacchetta J, Cochat P, Salusky IB, Wesseling-Perry K. The spectrum of renal osteodystrophy in children. Pediatr Nephrol. 2010;25(5):763-773.
15. Bakkaloglu SA. Bone disease and mineral metabolism in children with chronic kidney disease. Pediatr Nephrol. 2013;28(9):1519-1528.
16. Wesseling-Perry K, Pereira RC, Tseng CH, et al. Bone disease in pediatric hemodialysis patients. Pediatr Nephrol. 2014;29(2):285-292.
17. Greenbaum LA. Bone health in pediatric chronic kidney disease: impact and management. Pediatr Nephrol. 2012;27(1):13-22.
18. Salusky IB, Goodman WG. Adynamic bone disease in children with chronic kidney disease. Pediatr Nephrol. 2013;28(10):1951-1961.
19. Wesseling-Perry K, Pereira RC. The role of bone biopsy in pediatric CKD. Pediatr Nephrol. 2014;29(6):1043-1051.
20. Haffner D, Emma F, Molitoris BA, et al. Mineral and bone disorders in children with chronic kidney disease. Nat Rev Nephrol. 2022;18(1):51-68.
21. Bacchetta J, Ranchin B, Salusky IB, Wesseling-Perry K. Fibroblast growth factor 23 and Klotho in CKD-MBD. Pediatr Nephrol. 2015;30(12):2145-2153.
22. Shroff R, Donald AE, Hiorns M, et al. Vascular calcification and cardiovascular risk in children with chronic kidney disease. Pediatr Nephrol. 2010;25(9):1699-1706.
23. Civilibal M, Elevli M, Köksal Y, et al. The relationship between bone mineral density and vascular calcification in children with chronic kidney disease. Pediatr Nephrol. 2015;30(3):465-472.
24. Ott SM. Bone health in children with chronic kidney disease: assessment and management. Pediatr Nephrol. 2012;27(12):2249-2256.
25. Zemel BS, Kalkwarf HJ, Gilsanz V, et al. Assessment of bone health in children and adolescents with chronic kidney disease. J Bone Miner Res. 2011;26(12):2764-2772.

10.48047/jocaaa.2024.33.06.80

26. Rees L, Marks SD, Karet Frankl FE, et al. Bone disease in pediatric chronic kidney disease. Nat Rev Nephrol. 2020;16(9):539-556.
27. Ureña Torres P, D'Marco L, Raggi P, et al. Bone biomarkers in chronic kidney disease–mineral and bone disorder. Nat Rev Nephrol. 2021;17(4):251-266.
28. Wesseling-Perry K, Pereira RC. The role of bone biopsy in pediatric CKD. Pediatr Nephrol. 2014;29(6):1043-1051.
29. Bacchetta J, Cochat P, Salusky IB, Wesseling-Perry K. Bone biopsy for the evaluation of renal osteodystrophy in children. Curr Opin Nephrol Hypertens. 2013;22(4):439-444.
30. Leonard MB. Assessment of bone health in children and adolescents with CKD. J Bone Miner Res. 2017;32(4):823-831.
31. Bianchi ML. Bone health in children with chronic kidney disease. Bone. 2019;127:295-302.
32. Shaw NJ, Crabtree NJ. Practical considerations for bone densitometry in children. J Clin Densitom. 2014;17(2):258-264.
33. Gordon CM, Leonard MB, Zemel BS, International Society for Clinical Densitometry. 2013 ISCD Pediatric Position Development Conference: Executive Summary and Reflections. J Clin Densitom. 2014;17(2):219-224.
34. Zemel BS, Kalkwarf HJ, Gilsanz V, et al. Dual-energy X-ray absorptiometry in pediatric bone health assessment. J Clin Densitom. 2017;20(1):20-31.
35. Crabtree NJ, Shaw NJ, Bishop N, et al. Dual-energy X-ray absorptiometry interpretation and reporting in children and adolescents. J Clin Densitom. 2014;17(2):225-242.
36. Gordon CM, Leonard MB, Zemel BS, International Society for Clinical Densitometry. 2013 ISCD Pediatric Position Development Conference: Executive Summary and Reflections. J Clin Densitom. 2014;17(2):219-224.
37. Shepherd JA, Hangartner TN, Mazess RB, et al. Bone densitometry in children: Clinical practice guidelines. J Clin Endocrinol Metab. 2014;99(7):2477-2488.
38. Bianchi ML, Leonard MB, Bechtold S, et al. Interpretation of DXA in children and adolescents with CKD. Pediatr Nephrol. 2012;27(7):1129-1143.
39. Wren TA, Gilsanz V, Kalkwarf HJ, et al. Assessment of bone health in children: clinical and research considerations. J Bone Miner Res. 2014;29(8):1747-1755.
40. Schousboe JT, Shepherd JA, Bilezikian JP, Baim S. Advances in bone imaging for osteoporosis and CKD. Semin Nephrol. 2014;34(6):646-661.
41. Lima F, Chene G, Guillemin F. New technologies in bone densitometry and imaging. Endocrinol Metab Clin North Am. 2020;49(3):469-485.
42. Zemel BS, Kalkwarf HJ, Gilsanz V, et al. Height adjustment in the assessment of bone density in children. J Clin Endocrinol Metab. 2010;95(3):1265-1273.
43. Crabtree NJ, Shaw NJ, Bishop N, et al. Size-adjusted bone densitometry measurements in children. J Bone Miner Res. 2017;32(1):172-180.
44. Shaw NJ, Crabtree NJ. Practical considerations for bone densitometry in children. J Clin Densitom. 2014;17(2):258-264.
45. Shepherd JA, Hangartner TN, Mazess RB, et al. Bone densitometry in children: Clinical practice guidelines. J Clin Endocrinol Metab. 2014;99(7):2477-2488.
46. Ward LM, Konji VN, Ma J, et al. Reference standards for bone health assessment in children and adolescents. J Clin Densitom. 2014;17(2):275-282.

10.48047/jocaaa.2024.33.06.80

47. Bianchi ML, Leonard MB, Bechtold S, et al. Limitations of DXA for the assessment of bone health in children. Pediatr Nephrol. 2012;27(7):1129-1143.
48. Gordon CM, Leonard MB, Zemel BS, International Society for Clinical Densitometry. Pediatric bone densitometry: interpretation and clinical application. J Clin Endocrinol Metab. 2012;97(4):1137-1146.
49. Kalkwarf HJ, Zemel BS, Gilsanz V, et al. Defining normal bone mineral density in children. J Bone Miner Res. 2007;22(2):196-204.
50. Wesseling-Perry K, Pereira RC, Tseng CH, et al. Bone disease in pediatric hemodialysis patients. Pediatr Nephrol. 2014;29(2):285-292.
51. Bakkaloglu SA, Wühl E, Paglialonga F, et al. Management of bone health in children on dialysis. Pediatr Nephrol. 2019;34(11):2233-2244.
52. Greenbaum LA. Monitoring and treating bone disease in pediatric CKD. Pediatr Nephrol. 2012;27(1):13-22.
53. Leonard MB, Shults J, Zemel BS, et al. DXA as a tool for monitoring bone health in children with CKD. J Bone Miner Res. 2007;22(2):196-204.
54. Denburg MR, Leonard MB, Haynes K, et al. Fracture risk in pediatric chronic kidney disease: insights from DXA studies. J Bone Miner Res. 2016;31(10):1960-1967.
55. Shroff R, Wan M, Nagler EV, et al. Individualizing bone health management in children on hemodialysis. Pediatr Nephrol. 2020;35(2):237-249.
56. Gordon CM, Leonard MB, Zemel BS, International Society for Clinical Densitometry. Pediatric bone densitometry: interpretation and clinical application. J Clin Endocrinol Metab. 2012;97(4):1137-1146.
57. Shaw NJ, Crabtree NJ. Practical considerations for bone densitometry in children. J Clin Densitom. 2014;17(2):258-264.
58. Zemel BS, Kalkwarf HJ, Gilsanz V, et al. Height adjustment in the assessment of bone density in children. J Clin Endocrinol Metab. 2010;95(3):1265-1273.
59. Bianchi ML, Leonard MB, Bechtold S, et al. Limitations of DXA for the assessment of bone health in children. Pediatr Nephrol. 2012;27(7):1129-1143.
60. Kalkwarf HJ, Zemel BS, Gilsanz V, et al. Defining normal bone mineral density in children. J Bone Miner Res. 2007;22(2):196-204.
61. Ward LM, Konji VN, Ma J, et al. Reference standards for bone health assessment in children and adolescents. J Clin Densitom. 2014;17(2):275-282.
62. Crabtree NJ, Shaw NJ, Bishop N, et al. Size-adjusted bone densitometry measurements in children. J Bone Miner Res. 2017;32(1):172-180.
63. Leonard MB. Clinical interpretation of bone density in children with CKD. Pediatr Nephrol. 2007;22(2):181-193.
64. Gordon CM, Leonard MB, Zemel BS, International Society for Clinical Densitometry. Pediatric bone densitometry: interpretation and clinical application. J Clin Endocrinol Metab. 2012;97(4):1137-1146.
65. Wren TA, Gilsanz V, Kalkwarf HJ, et al. Assessment of bone health in children: clinical and research considerations. J Bone Miner Res. 2014;29(8):1747-1755.
66. Wetzsteon RJ, Kalkwarf HJ, Shults J, et al. Volumetric bone mineral density and bone geometry in pediatric CKD: comparison of DXA and QCT. J Bone Miner Res. 2009;24(3):473-480.
67. Bakkaloglu SA, Süsleyici-Duman B, Yildiz N, et al. pQCT in children with chronic kidney disease. Pediatr Nephrol. 2015;30(4):657-665.
68. Widmann G, Henninger B, Kasprian G, et al. MRI for bone and bone marrow assessment in pediatric patients. J Magn Reson Imaging. 2019;49(3):764-782.

10.48047/jocaaa.2024.33.06.80

69. Moyer-Mileur LJ, Slater H, Jordan KC, et al. Bone marrow composition and bone strength in pediatric CKD: MRI insights. J Bone Miner Res. 2017;32(7):1387-1397.
70. Jaworski M, Szpinda M, Słupski W, et al. Quantitative ultrasound in pediatric CKD: comparison with DXA. Pediatr Nephrol. 2015;30(11):2039-2046.
71. Gordon CM, Leonard MB, Zemel BS, International Society for Clinical Densitometry. Quantitative ultrasound for bone assessment in children and adolescents. J Clin Densitom. 2014;17(2):246-257.
72. Shaw NJ, Crabtree NJ. Practical considerations for bone densitometry in children. J Clin Densitom. 2014;17(2):258-264.
73. Bianchi ML. Bone health in children with chronic kidney disease. Bone. 2019;127:295-302.
74. Denburg MR, Leonard MB, Haynes K, et al. Fracture risk in pediatric chronic kidney disease: insights from DXA studies. J Bone Miner Res. 2016;31(10):1960-1967.
75. Shroff R, Wan M, Nagler EV, et al. Individualizing bone health management in children on hemodialysis. Pediatr Nephrol. 2020;35(2):237-249.
76. Leonard MB, Shults J, Zemel BS, et al. DXA as a tool for monitoring bone health in children with CKD. J Bone Miner Res. 2007;22(2):196-204.
77. Greenbaum LA. Monitoring and treating bone disease in pediatric CKD. Pediatr Nephrol. 2012;27(1):13-22.
78. Bianchi ML, Leonard MB, Bechtold S, et al. Interpretation of DXA in children and adolescents with CKD. Pediatr Nephrol. 2012;27(7):1129-1143.
79. Ott SM. Bone health in children with chronic kidney disease: assessment and management. Pediatr Nephrol. 2012;27(12):2249-2256.
80. Haffner D, Emma F, Molitoris BA, et al. Mineral and bone disorders in children with chronic kidney disease. Nat Rev Nephrol. 2022;18(1):51-68.
81. Gordon CM, Leonard MB, Zemel BS, International Society for Clinical Densitometry. 2013 ISCD Pediatric Position Development Conference: Executive Summary and Reflections. J Clin Densitom. 2014;17(2):219-224.
82. Bianchi ML, Leonard MB, Bechtold S, et al. Limitations of DXA for the assessment of bone health in children. Pediatr Nephrol. 2012;27(7):1129-1143.
83. Crabtree NJ, Shaw NJ, Bishop N, et al. Size-adjusted bone densitometry measurements in children. J Bone Miner Res. 2017;32(1):172-180.
84. Gordon CM, Leonard MB, Zemel BS, International Society for Clinical Densitometry. Pediatric bone densitometry: interpretation and clinical application. J Clin Endocrinol Metab. 2012;97(4):1137-1146.
85. Shaw NJ, Crabtree NJ. Practical considerations for bone densitometry in children. J Clin Densitom. 2014;17(2):258-264.
86. Zemel BS, Kalkwarf HJ, Gilsanz V, et al. Height adjustment in the assessment of bone density in children. J Clin Endocrinol Metab. 2010;95(3):1265-1273.
87. Shepherd JA, Hangartner TN, Mazess RB, et al. Bone densitometry in children: Clinical practice guidelines. J Clin Endocrinol Metab. 2014;99(7):2477-2488.
88. Leonard MB. Clinical interpretation of bone density in children with CKD. Pediatr Nephrol. 2007;22(2):181-193.
89. Kalkwarf HJ, Zemel BS, Gilsanz V, et al. Defining normal bone mineral density in children. J Bone Miner Res. 2007;22(2):196-204.
90. Schousboe JT, Shepherd JA, Bilezikian JP, Baim S. Advances in bone imaging for osteoporosis and CKD. Semin Nephrol. 2014;34(6):646-661.

10.48047/jocaaa.2024.33.06.80

91. Lima F, Chene G, Guillemin F. New technologies in bone densitometry and imaging. Endocrinol Metab Clin North Am. 2020;49(3):469-485.
92. Crabtree NJ, Shaw NJ, Bishop N, et al. Dual-energy X-ray absorptiometry interpretation and reporting in children and adolescents. J Clin Densitom. 2014;17(2):225-242.
93. Leonard MB, Shults J, Wilson BA, et al. Assessment of muscle and fat in children with CKD: implications for bone health. J Bone Miner Res. 2008;23(3):397-405.
94. Wetzsteon RJ, Shults J, Zemel BS, et al. HR-pQCT assessment of bone microarchitecture in pediatric CKD. Bone. 2011;48(2):242-247.
95. Widmann G, Henninger B, Kasprian G, et al. MRI for bone and bone marrow assessment in pediatric patients. J Magn Reson Imaging. 2019;49(3):764-782.
96. Kalkwarf HJ, Zemel BS, Gilsanz V, et al. Defining normal bone mineral density in children. J Bone Miner Res. 2007;22(2):196-204.
97. Crabtree NJ, Shaw NJ, Bishop N, et al. Size-adjusted bone densitometry measurements in children. J Bone Miner Res. 2017;32(1):172-180.