Original Article

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Quick Response Code:

Website: https://journals.lww.com/ijhm
DOI: 10.4103/ijh.ijh_113_25

Health-related quality of life, bone mineral density, and trabecular bone score of children with B-thalassemia major after bone marrow transplantation

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Abstract:

BACKGROUND: For children with serious hematologic, oncologic, and metabolic disorders, hematopoietic stem cell transplantation has significantly improved survival rates. Bone strength and fracture risk are indicated by bone mineral density (BMD), which quantifies the mineral content in bone tissue. Trabecular bone score (TBS) evaluates the microarchitecture and quality of bones.

OBJECTIVES: This study aimed to assess health-related quality of life (HRQoL) in children who received bone marrow transplantation (BMT) for beta-thalassemia major (β-TM) in a single center Kurdistan Region of Iraq.

MATERIALS AND METHODS: This retrospective cross-sectional study was carried out among 46 children previously diagnosed with β-TM who were receiving chelation therapy. Children who had previously had BMT were followed retrospectively to evaluate their outcomes. The BMD and TBS were used to measure the bone strength and fracture risk in children.

RESULTS: The mean age of the children was 15.02 (Range: 7–18 year), who underwent BMT at a mean age of 6.83 years. Boys comprised 52.17% of participants. HRQoL scores (out of 100%) were: total HRQoL (71.0%), physical (69.2%), emotional (61.3%), social (82.1%), and school (73.4%). Most had acceptable HRQoL (89.13%), especially in social functioning (95.65%). No gender differences were found in HRQoL or BMD, but boys had higher TBS than girls (1.46 vs. 1.34; $P = 0.0003$). BMD and TBS were within normal ranges. BMD was significantly higher in patients followed 6–15 years versus 1–5 years ($P = 0.000$). No significant correlations were found between BMD or TBS and HRQoL domains.

CONCLUSIONS: Children with β-TM who underwent BMT demonstrated overall good HRQoL and preserved bone health, with stable outcomes across follow-up periods. Emotional functioning remained the most affected domain, underscoring the importance of ongoing psychosocial support alongside routine clinical care.

Keywords:

Bone density, bone marrow transplantation, child, quality of life

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Submission: 01-09-2025
Revised: 27-09-2025
Accepted: 05-10-2025
Published: 05-01-2026

Introduction

Hematopoietic stem cell transplantation (HSCT), historically known as bone marrow transplantation (BMT), has dramatically increased the survival rate for pediatric patients with life-threatening hematologic, oncologic, and metabolic diseases.[1,2] While this aggressive procedure offers a potential cure, it is correlated to substantial morbidity that can impair survivors' recovery and adversely affect

How to cite this article: Aswad HA, Haleem AA, Eissaa AA. Health-related quality of life, bone mineral density, and trabecular bone score of children with B-thalassemia major after bone marrow transplantation. Iraqi J Hematol 2026;15:21-9.

their health-related quality of life (HRQoL).[3,4] As a result, HRQoL has become a critical metric for assessing the long-term consequences of transplantation, offering important information that goes beyond survival rates.[1,2] HRQoL is a dynamic and multifaceted concept reflecting an individual's subjective well-being across various dimensions, including physical, emotional, social, and functional health.[1,5] Understanding HRQoL in this vulnerable population is vital for informing patient education, evaluating supportive care interventions, and comprehending the profound impact of HSCT on patients' and their families' lives.[4]

The demanding nature of HSCT and its associated complications profoundly impact a child's HRQoL. Patients undergoing HSCT experience physiological and psychological demands that place them and their families at unique risk for altered HRQoL.[6] The process involves a prolonged hospitalization, followed by 6–12 months of protective isolation and chronic convalescence.[7] During this period, children are removed from normal activities and social environments, exacerbating feelings of emotional and social isolation.[7]

Findings on HRQoL in pediatric HSCT survivors are varied. Some studies suggest that the quality of life (QoL) of pediatric transplantation survivors is comparable to that of healthy peers.[1,8] In contrast, other research indicates that pediatric HSCT survivors' HRQoL can be worse than that of healthy peers or reference populations.[9] Physical functioning is consistently reported to be lower in posttransplant children compared to their healthy counterparts.[1] However, psychosocial functioning, including emotional and social domains, often becomes comparable to healthy peers after a period of recovery.[10]

Few studies have been conducted on HRQoL in thalassemia patients in Iraq. Of the two studies in Nineveh and Duhok reported that HRQoL in patients with transfusion-dependent beta-thalassemia major (β-TM) across various regions of Iraq is significantly reduced compared to healthy controls.[11-13] The most severely impacted domains are consistently the general health and energy/fatigue domains.[11,13] For Iraqi children and adolescents, the mean HRQoL is also markedly lower, with the lowest scores frequently observed in physical functioning.[14]

The Kurdistan Region of Iraq lacks data on HRQoL among pediatric HSCT survivors, despite unique regional factors that may significantly influence outcomes. These include financial constraints affecting healthcare access, political instability impacting service delivery, and cultural elements such as strong familial support – which may aid coping – but also potential stigma around chronic illness causing psychosocial stress. Variations in healthcare infrastructure, availability of specialized centers, and reliance on out-of-pocket payments further differentiate the region. This study addresses the gap by evaluating HRQoL and bone health in children post-BMT for β-TM at a single center in Kurdistan. It underscores the need for prospective, longitudinal research incorporating children's self-reports to better understand HRQoL trajectories. Findings aim to inform context-specific care strategies and enrich global knowledge on pediatric HSCT outcomes in underrepresented settings.

Materials and Methods

Study design and sampling

This retrospective cross-sectional work included children with a previous diagnosis of β-TM and undergoing chelation therapy who had undergone BMT. The cohort of participants, children with β-TM, were part of the Jeen Pediatric Hematology Oncology Center population in Duhok Governorate, Kurdistan Region of Iraq. The study was aimed specifically at children with β-TM who had received BMT. Patient data were collected from medical records to facilitate identification of individuals who received BMT and assessment of clinical outcome measures, retrospectively identified in the medical record from April 2024 to December 2024.

Inclusion and exclusion criteria

This study included children with β-TM of various ages and both genders, without additional specific inclusion criteria. All patients diagnosed with β-TM who underwent BMT between 2012 and the time of the study were included in the study. The only exclusion criteria were parental refusal to allow blood sample collection and the inclusion of adult patients. However, no instances of parental refusal were encountered during the study period.

Study setting

Patients were gathered from the "Jeen Pediatric Hematology Oncology Center" in the Kurdistan Region of Iraq's Duhok Governorate. This center is the only public facility in the region offering comprehensive diagnostic and treatment services for both pediatric and adult patients with hematologic and oncologic conditions. It serves a wide population across multiple districts within the governorate, including Duhok, Zakho, Semel, Amedi, Akre, Shekhan, and Bardarash. As no private medical centers in the area provide full oncology care, the center captures nearly all such cases in the region. Therefore, the study sample is considered representative of the target population.

Diagnosis of beta-thalassemia major

The Jeen Pediatric Hematology Oncology Center employs a comprehensive diagnostic approach for

beta-thalassemia, including complete blood count, hemoglobin electrophoresis, iron studies, and molecular genetic testing. Beta-thalassemia causes hypochromic, microcytic anemia, with severity depending on beta-globin gene mutations. Unlike alpha-thalassemia, iron overload – indicated by high serum ferritin – often occurs due to hemolysis, ineffective erythropoiesis, and transfusions. In beta-thalassemia minor, hemoglobin A2 (HbA2) is elevated (>3.2%–3.6%) with mild hemoglobin F (HbF) increase. In major/intermedia forms, HbA2 and HbF vary widely, sometimes with HbF >100%. Hb Lepore, a fusion variant, appears as an abnormal electrophoretic band and mimics thalassemia hematologically.[15]

Outcome measurements

General and medical information for the patients was recorded in their medical records at the Jeen Pediatric Hematology Oncology Center, which has documentation for all patients with β-TM as a part of their routine registration and follow-up. Blood samples were collected from the participants by the research team and transported to a medical laboratory for further analysis.

Pediatric quality of life inventory

The pediatric quality of life inventory (PedsQL) parent-proxy version is a standardized tool for assessing children's HRQoL from the caregiver's perspective. It is available for different age groups (2–4, 5–7, 8–12, and 13–18 years) and includes 23 items divided into four domains: physical, emotional, social, and school functioning. Parents rate how often problems occur over the past month, using a 5-point Likert scale (0 = never to 4 = almost always), with a simplified 3-point scale for younger children. Scoring involves reversing and transforming responses to a 0–100 scale, where higher scores reflect better QoL (e.g., 0 = 100, 4 = 0). Domain scores are calculated as the mean of completed items, and an overall score is derived from all items. If over 50% of items are missing, the scale score is not computed. The PedsQL parent version is widely validated for clinical and research use.[16] HRQoL scores were dichotomized into "acceptable" and "lower" based on a previously established cutoff of <70 for the total score.[17]

Transplant procedure and follow-up plan

Our facility has treated a total of 102 patients, consisting of 48 adults and 54 children, who subsequently underwent BMT. Of those patients who underwent BMT, 15 had treatment failure, and 5 patients died. Of 52 pediatric patients were eligible for this study, 5 were treated at the King Hussein Cancer Center in Jordan, 23 were treated in several hospitals in India–BLK-Max Super Speciality Hospital, NH Mazumdar Shaw Cancer Center, and MAX Hospital, 13 were treated in Turkey at Medical Park Hospital and Medipol Mega University Hospital, and 5 were in Italy at IRCCS Ospedale San Raffaele and Hospital Binaghi, and 5 were in the Kurdistan Region of Iraq at Hiwa Hospital. The type of donor was a matched sibling, but the conditioning regimen was unknown. The overall treatment failure (recurrence) rate was 15 of 102 patients (14.71%), and the mortality rate was 4.90%. We were not able to reach all patients to assess the HRQoL for this study. In the end, for the HRQoL aim of this study, we enrolled 46 patients.

Statistical analysis

This study analyzed general and medical characteristics of children with β-TM using descriptive statistics: frequencies (%) for categorical variables and mean ± standard deviation for continuous variables. Normality was assessed through Q-Q plots. Gender differences in clinical and bone health parameters (bone mineral density [BMD], trabecular bone score [TBS]) were examined using *t*-tests and Chi-squared tests. HRQoL prevalence post-BMT was reported by gender. Changes in health-related HRQoL over time were assessed with one-way ANOVA, and associations between BMD, TBS, and HRQoL domains were explored using Pearson correlation analysis. Statistical significance was set at $P < 0.05$, with analyses conducted in JMP® Version 18 (2025 JMP® 18. JMP Statistical Discovery LLC, Cary, NC).

Ethical approval

Ethical approval for the study was obtained from the Medical Ethics Council of the General Directorate of Health in Duhok. Informed consent was obtained from the parents or legal guardians of all participating children. The study protocol was registered on August 28 2024, under reference number 28082024-7-9.

Results

The mean age of the children was 15.02, ranging between 7 and 18 years old. The mean values of the height, weight, and body mass index were 154.61 cm, 52.05 kg, and 21.39, respectively. The mean age of the children at the time of the BMT was 6.83 years, between 3 and 15 years. The patients were boys (52.17%) and girls (47.83%). The patients were followed up at different time periods, including 1–5 years (15.22%), 6–10 years (71.74%), and 11–15 years (13.04%). The age of the children at BMT was 3–5 years (39.13%) and 6–15 years [60.87%; Table 1].

The mean values of the total HRQoL, physical functioning, emotional functioning, social functioning, and school functioning were 71.0, 69.2, 61.3, 82.1, and 73.4 of 100. There was no significant difference in the total HRQoL ($P = 0.6055$), physical functioning ($P = 0.1177$), emotional functioning ($P = 0.8410$), social functioning ($P = 0.7345$), and school functioning ($P = 0.3952$) between boys and girls. In addition, there was no significant

difference in the BMD level between boys and girls ($P = 0.1004$). However, the boys have a significantly higher mean value of TBS compared to the girls (1.46 vs. 1.34; $P = 0.0003$). The BMD and TBS of all patients were located in the normal values [Table 2 and Figure 1]. While most domains scored well, emotional functioning was the lowest rated domain (43.48%), with over one-fifth (21.74%) of patients scoring in the "lower" range [Table 3 and Figure 2].

The study showed that the mean values of the total HRQoL and its domains were not significantly different in patients who were followed up in different time periods. The mean values of the TBS were similar across different follow-up times ($P = 0.4047$). However, the children who were followed-up at longer (6–10 years and 11–15 years) time had significantly higher mean value of BMD compared to those children who were followed-up between 1 and 5 years [$P = 0.000$; Table 4].

The study showed that the BMD and TBS were not significantly correlated with HRQoL and its domains in children with beta-thalassemia after BMT [Table 5].

Table 1: General and medical characteristics of the beta-thalassemia major who received bone marrow transplantation

Characteristics (n=46)	Ferency distribution, mean±SD
Age (7–18 years), SEM: 0.47	15.02±3.17
Height (cm)-adj	154.61±11.62
Weight (kg)	52.05±17.61
BMI	21.39±5.71
Age at time of BMT (3–15 years)	6.83±2.74
Gender	
Male	24 (52.17)
Female	22 (47.83)
Follow-up category (years)	
1–5	7 (15.22)
6–10	33 (71.74)
11–15	6 (13.04)
Age at time of BMT category (years)	
3–5	18 (39.13)
6–15	28 (60.87)

BMI=Body mass index, SEM=Standard error of mean, SD=Standard deviation, BMT=Bone marrow transplantation

Discussion

The current study investigated the long-term HRQoL and bone health outcomes in pediatric bone marrow transplant (BMT) survivors, providing valuable insights into their posttransplant well-being. The cohort, with a mean age of 15.02 years at the time of the study and a mean age of 6.83 years at BMT, consisted of slightly more boys (52.17%) than girls (47.83%), with most transplants occurring between 6 and 15 years of age. Overall, the findings present a largely favorable picture of stable HRQoL and improving bone health over time, although specific domains and gender differences warrant closer examination in the context of existing literature.

Demographics and transplant characteristics

The mean age at BMT in this study (6.83 years) falls within the typical pediatric range studied in the literature, which often includes children from infancy up to 18 or 21 years.[18,19] Studies on HSCT, often used interchangeably with BMT,[20] consistently highlight age at transplant as a crucial factor influencing various long-term outcomes, including growth.[21] The finding that most patients received BMT between 6 and 15 years is consistent with the age range for school-aged children, often included in HRQoL assessments.[18] The slight male preponderance in the study (52.17% boys) aligns with some demographic trends in pediatric cancer incidence.[22]

Health-related quality of life outcomes

Overall health-related quality of life and subscale scores

The study reports an acceptable total HRQoL score of 71.0 (out of 100). This generally positive finding resonates with a significant portion of the literature, which suggests that many pediatric BMT/HSCT survivors report good to excellent HRQoL.[2,20,23] For instance, one study found that HSCT survivors had an equivalent HRQoL to their healthy peers in all domains except physical functioning.[1] Similarly, another study reported that 75% of patients demonstrated no physical or psychological impairment on an HRQoL questionnaire, and 75% reported an excellent HRQoL.[2,24] The long-term HRQoL

Table 2: Total health-related quality of life and its domains in children with the beta-thalassemia after bone marrow transplantation between genders

QoI and BMD	Frequency distribution				P
	Mean±SD	Minimum–Maximum	Male	Female	
Total QoL	71.0±16.8	34.8–100	72.2±14.8	69.6±19.0	0.6055
Physical functioning	69.2±20.8	21.9–100	73.8±15.8	64.2±24.5	0.1177
Emotional functioning	61.3±19.8	20.0–100	61.9±18.7	60.7±21.4	0.8410
Social functioning	82.1±17.5	40.0–100	82.9±16.1	81.1±19.2	0.7345
School functioning	73.4±24.0	0.0–100	70.4±25.3	76.7±22.6	0.3952
BMD	0.83±0.16	0.48–1.28	0.87±0.18	0.79±0.12	0.1004
TBS	1.40±0.12	0.93–1.70	1.46±0.09	1.34±0.12	0.0003

An independent t-test was performed for statical analyses. BMD=Bone mineral density, QoL=Quality of life, TBS=Trabecular bone score, SD=Standard deviation

in adult patients who underwent HSCT in childhood was also found to be good and comparable to healthy population norms.[25] However, some studies have reported more mixed findings or poorer HRQoL in specific subgroups or time points.[2,6,26]

Emotional functioning

The emotional functioning score (61.3) was the lowest among all HRQoL domains, and emotional functioning had the highest rate of impairment (21.74%). This is a critical finding, as emotional well-being is a frequently impacted area in BMT survivors. Several sources identify a prevalence of psychological symptoms following BMT, including anxiety, nervousness, tension, mood disturbances, and depression.[10,20] Fear of relapse is a common worry among survivors and their parents, affecting 25%–75% in some studies. Children may also experience feelings of inadequacy, conduct problems, and perfectionism.[2] Parental reports have also indicated significantly lower mental health scores for their children compared to the children's self-reports.[18,20] The acute phase of HSCT is associated with increased sadness and worry, impacting HRQoL for several months.[27] Given the noted impairment, targeted psychosocial support

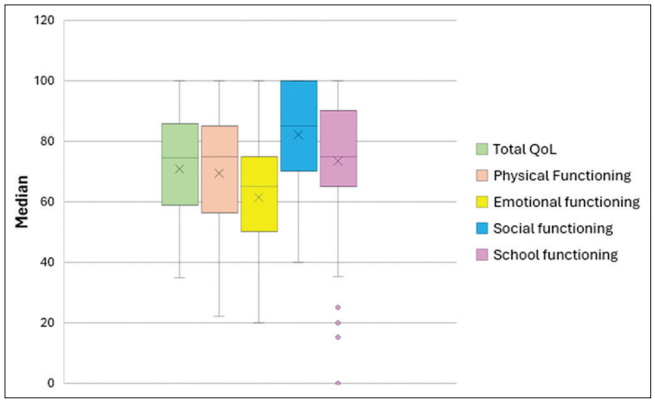

Figure 1: Mean and median values of quality of life and domains of all patients. QoL: Quality of life

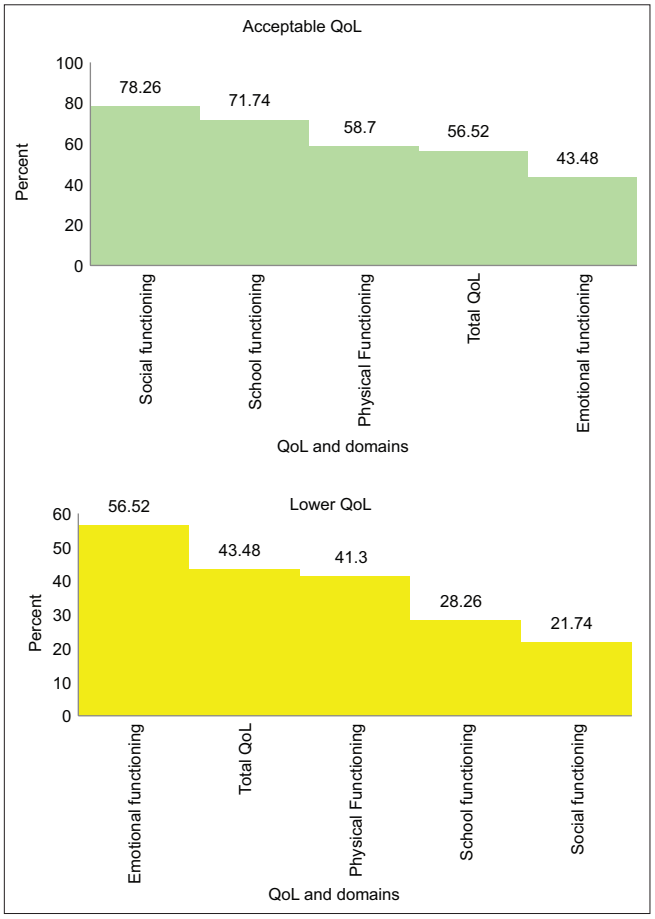

Figure 2: Lower and acceptable levels of quality of life and domains in all patients. QoL: Quality of life

Table 3: Prevalence of the acceptance level of quality of life in children with the beta-thalassemia after bone marrow transplantation between genders

QoL	All patients, *n* (%)	Gender		*P*
		Male (*n*=24), *n* (%)	Female (*n*=22), *n* (%)	
Total QoL				
Lower	20 (43.48)	10 (21.74)	10 (21.74)	1.000
Acceptable	26 (56.52)	14 (30.43)	12 (26.09)	
Physical functioning				
Lower	19 (41.30)	7 (15.22)	12 (26.09)	0.0808
Acceptable	27 (58.70)	17 (36.96)	10 (21.74)	
Emotional functioning				
Lower	26 (56.52)	15 (32.61)	11 (23.91)	0.3929
Acceptable	20 (43.48)	9 (19.57)	11 (23.91)	
Social functioning				
Lower	10 (21.74)	5 (10.87)	5 (10.87)	1.0000
Acceptable	36 (78.26)	19 (41.30)	17 (36.96)	
School functioning				
Lower	13 (28.26)	8 (17.39)	5 (10.87)	0.5207
Acceptable	33 (71.74)	16 (34.78)	17 (36.96)	

Fisher's exact test was performed for statistical analyses. QoL=Quality of life

Table 4: Total health-related quality of life and its domains in Children with the beta-thalassemia after BMT between follow-up times

QoI and BMD	Follow-up cat Mean (Std Dev)			*P* (Pairwise)
	1-5 years	6-10 years	11-15 years	
Total QoL	72.8 (19.8)	69.0 (17.3)	79.5 (5.3)	0.3581
Physical Functioning	70.1 (17.9)	66.3 (21.8)	84.4 (11.7)	0.1454
Emotional functioning	65.7 (20.1)	60.8 (21.2)	59.2 (12.0)	0.8089
Social functioning	83.6 (21.2)	79.4 (17.4)	95.0 (6.3)	0.1283
School functioning	73.6 (27.8)	72.7 (25.1)	76.7 (14.4)	0.9375
BMD	0.6 (0.1)	0.9 (0.1)	0.9 (0.1)	0.0002
				11-15 years >1-5 years (*P*=0.0015)
				6-10 years >1-5 years (*P*=0.0002)
TBS	1.4 (0.1)	1.4 (0.1)	1.5 (0.1)	0.4047

One-way ANOVA was performed for statistical analyses

Table 5: Correlations of BMD and TBS with QoL and its domains in children with the beta-thalassemia after BMT between follow-up times

BMD and TBS	QoL and domains *r* (*P*)				
	Total QoL	Physical Functioning	Emotional functioning	Social functioning	School functioning
BMD	-0.07 (0.63)	0.09 (0.56)	-0.19 (0.20)	0.01 (0.96)	-0.16 (0.31)
TBS	0.03 (0.85)	0.11 (0.48)	-0.10 (0.53)	0.00 (0.99)	0.10 (0.54)

Pearson correlation was performed for statistical analyses

interventions for emotional health are clearly indicated for this population.[28]

Physical functioning

The physical functioning score (69.2) also indicates room for improvement compared to other domains. Physical side effects and disturbances are common after BMT, with one study reporting 84% of children having physical disturbances at least 6 months post-BMT.[29] Young adult survivors of childhood BMT have shown significantly lower general health compared to healthy individuals.[20] Patients often report worse physical functioning immediately post-BMT, with the highest expressions evidenced for running and exercise.[26] Impairments in physical function during the 1st year post-HSCT are particularly notable.[30] However, some studies indicate that physical functioning improves over time.[31] The observed score, while acceptable, suggests ongoing challenges that may require attention, especially in the early posttransplant period or with the resumption of normal activities, where functional limitations become more apparent.[18]

Social and school functioning

The relatively high scores for social functioning (82.1) and school functioning (73.4) are positive indicators. Many studies show that BMT survivors successfully re-establish social relationships and return to school.[28,29] Improvements in emotional and social functioning are often observed over time, contributing positively to overall development.[32] While some studies initially report learning problems [29] or reduced school attendance due to isolation[33], generally good scores here suggest successful reintegration into these crucial life domains for most children in the study.

Gender differences in health-related quality of life

The study found no significant gender differences in HRQoL domains. This contrasts with some literature, which has reported females having lower mean scores in domains such as sexual functioning, psychological distress, and extended family relationships.[28] Girls have also been found to report lower HRQoL scores than boys during BMT recovery in some studies.[34] However, other studies have found no significant relation between sex and HRQoL.[34] This variability highlights the complexity of gender as a determinant of HRQoL post-BMT.

Health-related quality of life over follow-up periods

The finding that HRQoL did not differ significantly over follow-up periods suggests a stable, generally acceptable level of HRQoL is maintained over time for these survivors. This aligns with studies showing that overall HRQoL stabilizes or improves to levels comparable to healthy peers in the long term.[1] While initial declines in HRQoL are often observed during the acute phase of transplant, followed by gradual improvement[6], the stability across followup periods in this study suggests that those who navigate the initial recovery maintain a consistent level of wellbeing in the subsequent years.

Bone health outcomes (bone mineral density and trabecular bone score)

Overall bone health

The study's results indicate that both BMD and TBS remained within normal ranges. This is an encouraging finding, as diminished BMD is a known complication after BMT in children.[19,35] Endocrine dysfunction, irradiation, corticosteroids, and chronic graft-versus-host disease (cGVHD) are all identified as risk factors for

diminished BMD.[36,37] While osteoporosis is common in children with chronic inflammatory diseases, and vertebral involvement is frequent even without a fracture history,[38] this study suggests that in this cohort, overall bone health is well-maintained. This could be influenced by the age at BMT, the specific conditioning regimens used, and posttransplant care.

Gender differences in trabecular bone score

A notable finding is that boys had significantly higher TBS than girls (1.46 vs. 1.34; $P = 0.0003$). This indicates a gender-specific difference in bone micro-architecture, even though both sexes remained within normal ranges. This aligns with literature suggesting female sex as a risk factor for diminished BMD and lower volumetric *Z*-scores. Compromised BMD after BMT is an even greater concern for female survivors, as osteoporosis and osteopenia are major health concerns in healthy older females.[19] These findings underscore the importance of gender-specific monitoring and potentially interventions for bone health in this population.

Bone mineral density over follow-up periods

The study observed that BMD was significantly higher in patients followed up 6–15 years post-BMT compared to those followed 1–5 years ($P = 0.000$). This is a very positive outcome, suggesting improving bone health over time in pediatric BMT survivors. This contrasts with some studies that show a lowest BMD of the femoral neck observed 24 months after transplantation.[39] However, it supports the general notion that long-term outcomes can improve, especially if the initial status was not severely compromised.[39] Some studies have reported a positive correlation between the time elapsed since HSCT and vitamin D levels, as well as an improvement in BMD over timethe findings that further support the possibility of bone health recovery after HSCT.[40] The significant improvement in BMD over time is encouraging and may reflect recovery from transplant-related insults, resolution of iron overload posttransplant, or age-appropriate catch-up growth.

Lack of Correlation between Bone mineral density/trabecular bone score and health-related quality of life

The absence of significant correlations between BMD or TBS and any HRQoL domain is an intriguing finding. However, given that both BMD and TBS were within normal ranges in this cohort, and a high rate of severe impairment in emotional functioning was noted, it is plausible that psychological and emotional factors might exert a more dominant influence on overall HRQoL than bone health, especially if bone health issues are subclinical or well-managed.

Role of family

The family is foundational to improving the HRQoL for children with thalassemia.[41] Family support has a significant correlation with QoL, providing essential care and helping to reduce the stress associated with this chronic illness. This positive family involvement is crucial for increasing treatment compliance. When family members provide appreciation and attention, they encourage children to feel comfortable, braver, and happier.[42]

Beyond emotional care, socioeconomic factors such as family income and parental education directly influence the child's HRQoL.[41] A positive correlation also exists between the parents' psychological well-being and the child's HRQoL. Moreover, interventions such as the family-centered empowerment model have demonstrated success in significantly improving the overall QoL across physical, emotional, social, and school dimensions.[43]

Overall implications and future directions

The scale used in this study may not fully capture the HRQoL of the children. However, it is the only available instrument that allows researchers to assess HRQoL across such a wide age range. In addition, the children were treated at different centers across multiple countries, which may have affected their overall quality of care and recovery. In addition, heterogeneity in transplant protocols across different countries, the relatively small sample size limiting subgroup analyses, and the cross-sectional design, which prevents establishing causality, could be considered additional study limitations.

This study highlights positive long-term HRQoL and improving bone health in pediatric BMT survivors, indicating strong resilience and biological recovery. However, emotional functioning emerged as the most impaired domain, underscoring the need for ongoing psychosocial support and routine mental health screening. Physical functioning, while acceptable, requires continued monitoring. Gender differences in TBS suggest female survivors may need tailored bone health interventions. Integrating standardized HRQoL and bone assessments into follow-up care is essential. Future research should adopt multisite, longitudinal designs with larger samples to examine conditioning regimens, cGVHD, and endocrine factors, whereas incorporating qualitative insights to deepen understanding of survivors' experiences and improve post-BMT care.

Conclusions

This study highlights that pediatric BMT survivors in the Kurdistan Region generally achieve favorable long-term

outcomes in both HRQoL and bone health, with resilience evident in most domains and improvements in BMD over time. However, persistent emotional challenges and gender-specific differences in bone parameters emphasize the need for integrated follow-up strategies that combine psychosocial support, tailored bone health monitoring, and patient-centered quality-of-life assessments. Future multicenter, longitudinal research using child self-reports is essential to validate these findings and optimize survivorship care.

Financial support and sponsorship
Nil.

Conflicts of interest
There are no conflicts of interest.

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