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Xuefeng Xie
Shenzhen Second People's Hospital
Hulu Xia
Shenzhen Second People's Hospital
Lifen Zeng
Shenzhen Second People's Hospital
Jinrong Yu
Shenzhen Second People's Hospital
Lili Meng
Shenzhen Second People's Hospital
Fan Huang
Shenzhen Second People's Hospital
Shufen Song
Shenzhen Second People's Hospital
Jinghua Liang
hualady1220@126.com
Shenzhen Second People's Hospital

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Title Page

Network structure of family management dimensions and psychosocial resources in families of children with transfusion-dependent beta-thalassemia

Xuefeng Xie[1†], **Hulu Xia**[1†], Lifen Zeng[1], Jinrong Yu[1], Lili Meng[1], Fan Huang[1], Shufen Song[2*], Jinghua Liang[1*]

† These authors contributed equally as first authors.

* These authors contributed equally as corresponding authors.

Author affiliations:

[1] Department of Paediatrics, The First Affiliated Hospital of Shenzhen University, Shenzhen Second People's Hospital, Sungang West Road No. 3002, Shenzhen, 518035, Guangdong Province, China.

[2] Department of Obstetrics, Gynecology and Paediatrics, The First Affiliated Hospital of Shenzhen University, Shenzhen Second People's Hospital, Sungang West Road No. 3002, Shenzhen, 518035, Guangdong Province, China.

Corresponding authors:

Jinghua Liang, Department of Paediatrics, The First Affiliated Hospital of Shenzhen University, Shenzhen Second People's Hospital, Sungang West Road No. 3002, Shenzhen, 518035, Guangdong Province, China. E-mail: hualady1220@126.com. ORCID: 0009-0003-0629-9533.

Shufen Song, Department of Obstetrics, Gynecology and Paediatrics, The First Affiliated Hospital of Shenzhen University, Shenzhen Second People's Hospital, Sungang West Road No. 3002, Shenzhen, 518035, Guangdong Province, China. E-mail: songsfwill@126.com.

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Abstract

Background

Families of children with transfusion-dependent β-thalassemia face ongoing challenges in disease management and family functioning. Family management and psychosocial resources may interact as a complex system, but their interrelationships remain insufficiently understood. This study aimed to examine the network structure of family management and psychosocial resources in families of children with transfusion-dependent β-thalassemia and to identify central and bridge nodes.

Methods

A cross-sectional study was conducted among primary caregivers of children with transfusion-dependent β-thalassemia. Of 214 caregivers initially recruited, 195 with complete data on 12 predefined network nodes were included in the final analysis. The network comprised six dimensions of the Chinese version of the Family Management Measure, together with disease knowledge, parenting self-efficacy, family intimacy, and three dimensions of perceived social support. A Gaussian graphical model was estimated using Graphical LASSO. Strength, Expected Influence, and Bridge Strength were calculated. Edge robustness and centrality stability were examined using bootstrap procedures.

Results

The network showed both within-community clustering and between-community connections. The strongest positive edges were observed between *SS: Friends* and *SS: Others* (partial correlation = 0.470), *Family Intimacy* and *SS: Family* (0.410), *FM: Family Life Difficulty* and *FM: Management Burden* (0.407), and *FM: Condition-Related Worry* and *FM: Family Life Difficulty* (0.371). The strongest negative edge was found between *FM: Child Daily Life* and *FM: Family Life Difficulty* (-0.331). *FM: Family Life Difficulty* had the highest Strength centrality (1.491), whereas *FM: Parental Mutuality* had the highest Bridge Strength (0.922). The correlation stability coefficient was 0.50 for both Strength and Bridge Strength, indicating good stability.

Conclusions

FM: Family Life Difficulty was the most central node in the network, and *FM: Parental Mutuality* was the key bridge node linking family management and psychosocial resources. These findings suggest that reducing family life difficulty and strengthening parental mutuality may be important targets for family-based interventions in transfusion-dependent β-thalassemia.

Keywords

transfusion-dependent β-thalassemia; family management; psychosocial resources; network analysis; caregivers

1. Background

β-Thalassemia is among the most prevalent hereditary hemolytic anemias worldwide, with a particularly high burden in the Mediterranean basin, the Middle East, Southeast Asia, and southern China[1]. While the global gene carrier rate is approximately 1.5% [2], the prevalence in mainland China is notably higher at 2.21%[3], reflecting a significant public health challenge in the region. Transfusion-dependent β-thalassemia (TDT), the most severe phenotype, is characterized by a near-complete absence of functional hemoglobin synthesis, necessitating lifelong regular red blood cell transfusions[4]. Although advances in transfusion protocols and iron chelation therapy have substantially extended life expectancy, TDT remains incurable for most children who are ineligible for hematopoietic stem cell transplantation(HSCT)[5]. HSCT represents the only currently available curative option; however, its application remains limited by the scarcity of compatible donors, the risk of transplant-related complications, and the prohibitive costs associated with the procedure, particularly in resource-constrained settings in southern China[6]. As a result, families must navigate an unrelenting treatment regimen, including scheduled transfusions every two to four weeks, daily iron chelation therapy, and vigilant monitoring for multiorgan complications[7]. Beyond the medical demands, this unremitting treatment trajectory imposes substantial psychosocial burdens on families, disrupting parental employment, family routines, and sibling relationships, and creating an environment in which effective family management and adequate psychosocial resources become indispensable for sustaining family functioning[8].

Family management of childhood chronic conditions has emerged as a critical framework for understanding how families perceive, organize, and respond to the

challenges posed by pediatric illness[9]. The Family Management Measure (FaMM), developed by Knafl and colleagues, provides a theoretically grounded assessment of six distinct dimensions: Child's Daily Life, Condition Management Ability, Condition Management Effort, Family Life Difficulty, Parental Mutuality, and View of Condition Impact[10]. The FaMM has been validated in multiple cultural contexts, demonstrating robust psychometric properties[11]. The Chinese version of the FaMM used in the present study demonstrated good internal consistency (Cronbach's $\alpha = 0.86$) and satisfactory construct validity, supporting its suitability for use in mainland Chinese populations[12]. Its applicability has further been established across multiple pediatric chronic-illness populations, including childhood cancer[13], asthma[11], and thalassemia[14].

For instance, Abuelela reported that thalassemia families with higher Condition Management Ability and stronger Parental Mutuality scores demonstrated better health-related quality of life in affected children, underscoring the clinical relevance of these dimensions as potential intervention targets—a gap that the present study seeks to extend by mapping their systemic interrelationships[14].

Psychosocial resources—including disease knowledge, parenting self-efficacy, family intimacy, and perceived social support—represent modifiable factors that may play a protective role in family adaptation to the chronic demands of TDT caregiving, a context in which depression has been reported in 20.5% to 35% of caregivers[8].

Although family management dimensions and psychosocial resources have each been examined independently in thalassemia research, their co-examination within a unified analytical framework remains limited. Moreover, the interrelationships between these two domains have been investigated almost exclusively using conventional regression-based methods, which cannot capture the simultaneous, mutually conditioning interactions among all variables as a system—a critical limitation given that, in clinical reality, these variables co-evolve within a web of interdependencies that pairwise regression cannot adequately represent. Consequently, the pattern of associations and interrelationships among these variables, and their collective role in family adaptation to TDT, remains insufficiently characterized.

Network analysis, specifically Gaussian graphical models estimated with regularization approaches such as Graphical LASSO (GLASSO), provides a statistically rigorous alternative that maps partial correlation structures among all variables simultaneously, preserving unique pairwise associations after controlling for all other nodes[15]. Originally developed in psychopathology research by Borsboom and colleagues[16], network analysis has been progressively applied to health psychology and nursing science, including studies of caregiver burden, chronic disease self-management, and quality of life[17-20]. Within network frameworks, centrality indices such as Strength and Expected Influence identify the most influential nodes, while bridge centrality indices identify nodes that span conceptually distinct communities and mediate cross-domain transmission of influence[21]. Nodes with high centrality or bridge centrality are theoretically predicted to exert the greatest leverage on the broader network when targeted by intervention [21].

To date, no study has simultaneously mapped the internal structure of family management dimensions and their connections with psychosocial resources in TDT families using network analysis, leaving the bridge architecture linking these two domains entirely uncharacterized. Conventional regression-based approaches estimate each pairwise association while adjusting for a fixed set of covariates, but they cannot isolate the unique partial correlation between any two variables after controlling for all other family management and psychosocial variables concurrently. Network analysis with a Gaussian graphical model overcomes this limitation by estimating a sparse partial correlation network in which each retained edge represents an association that persists after conditioning on every other node in the system. Moreover, bridge centrality—a metric without a direct analogue in regression or structural equation modeling—quantifies the extent to which a node connects two conceptually distinct communities (e.g., family management versus psychosocial resources). A node with high bridge strength is hypothesized to serve as a cross-domain conduit, making it a theoretically prioritized target for interventions aiming to produce spillover effects across domains. Consequently, clinicians and intervention designers currently lack an evidence-based rationale for selecting which family-level variables to prioritize.

This study applies network analysis to construct a partial correlation network of the six FaMM dimensions and six psychosocial resource variables... we aim to: (1) delineate the overall network structure and edge patterns among family management dimensions and psychosocial resources; (2) identify the most influential (high-centrality) and

bridge nodes linking family management and psychosocial resources—an analytic objective unattainable through regression-based approaches alone; and (3) generate network-informed hypotheses regarding high-priority targets for family-centered interventions, with particular attention to nodes exhibiting high bridge centrality as candidate leverage points for cross-domain intervention effects.

2. Methods

2.1 Study design and setting

This was a single-center cross-sectional study conducted in the inpatient department of Pediatrics, Shenzhen Second People's Hospital from June 2025 to November 2025. This study aimed to examine the network structure of family management dimensions and psychosocial resources in families of children with transfusion-dependent β-thalassemia, and to identify central and bridge nodes within the network.

2.2 Participants and data collection

Participants were recruited via convenience sampling.
Inclusion criteria: ① Children were diagnosed with transfusion-dependent β-thalassemia by hemoglobin electrophoresis and genetic testing, had received regular transfusion therapy for ≥6 months, and were aged ≤18 years; ② Caregivers were the primary daily caregivers of the children (providing care for ≥8 hours per day for at least 3 consecutive months) and were aged ≥18 years; ③ Caregivers had clear consciousness, basic literacy, and the ability to complete the questionnaire independently; ④ Caregivers provided informed consent and volunteered to participate in the study.
Exclusion criteria: ① Children complicated with other severe congenital diseases, malignant tumors, or neuropsychiatric disorders; ② Questionnaires with >10% missing items or systematic invalid responses.

A total of 214 caregivers were initially recruited. Since the Parental Mutuality dimension of the Chinese version of the Family Management Measure is only applicable to caregivers with a spouse, only participants with complete data on all 12 predefined network nodes were included in the final network analysis. After excluding participants with invalid data for this spouse-specific dimension or missing values in the selected node variables, 195 participants were finally retained for analysis.

Data were collected using a structured questionnaire covering sociodemographic characteristics, clinical information, family management patterns, disease knowledge, parenting self-efficacy, family intimacy, and perceived social support.

2.3 Measures

2.3.1 Sociodemographic and clinical characteristics

Sociodemographic and clinical variables included child age, sex, body mass index, number of minor children in the household, pre-transfusion hemoglobin level at the most recent transfusion, age at first iron chelation, parental age, parental education level, and parental employment status.

2.3.2 Family management

Family management was assessed using the Chinese version of the Family Management Measure (FaMM), which was translated and validated by Yang et al. based on the original scale developed by Knafl and colleagues.[12] Grounded in the family management style framework, the FaMM evaluates how families perceive, organize, and respond to the child's chronic condition in daily life. The original FaMM comprises six dimensions: Child's Daily Life, Condition Management Ability, Condition Management Effort, Family Life Difficulty, Parental Mutuality, and View of Condition Impact. The Chinese version has demonstrated acceptable to good internal consistency across dimensions, with Cronbach's α coefficients ranging from 0.65 to 0.87, and satisfactory construct validity in Chinese pediatric chronic disease populations[12].

In the present study, six dimensions of the Chinese version FaMM were included as network nodes. For conciseness in network presentation, Condition Management Effort is referred to as Management Burden, and View of Condition Impact is referred to as Condition-Related Worry throughout the paper. The six dimensions are: Child Daily Life, Management Ability, Parental Mutuality, Condition-Related Worry, Family Life Difficulty, and Management Burden. The Parental Mutuality dimension is applicable only to caregivers with a spouse.

2.3.3 Disease knowledge

Disease-related knowledge was assessed using a transfusion-dependent β-thalassemia disease knowledge questionnaire, which evaluates caregivers' understanding of disease inheritance, complications, transfusion, iron chelation, and long-term management[5]. The total score was used in the network analysis as Disease Knowledge.

2.3.4 Parenting self-efficacy

Parenting self-efficacy was measured using the Parenting Self-Efficacy Scale[40]. The total score was used in the network analysis as Parenting Self-Efficacy.

2.3.5 Family intimacy

Family intimacy was measured using the Family Intimacy Scale[39]. The total score was used in the network analysis as Family Intimacy.

2.3.6 Perceived social support

Perceived social support was assessed using the Perceived Social Support Scale[38]. Three subscale scores were included in the network analysis: Family, Friends, and Others.

For all instruments, total scores or subscale scores were calculated according to the original scoring instructions, and reverse-scored items were handled as required. These scale-derived scores, rather than individual item scores, were used as nodes in the network model.

2.4 Network node specification

A total of 12 variables were included as network nodes. Based on the family management style framework [9, 10], the six FaMM dimensions were conceptually grouped into two communities: an FM–Adaptation community (FM: Child Daily Life, FM: Management Ability, and FM: Parental Mutuality) reflecting family adaptive capacities, and an FM–Burden community (FM: Condition-Related Worry, FM: Family Life Difficulty, and FM: Management Burden) capturing disease-related stressors. The remaining six variables formed the Psychosocial Resources community (Disease Knowledge, Parenting Self-Efficacy, Family Intimacy, SS: Family, SS: Friends, and SS: Others), consistent with prior network studies grouping resource-related variables into a single community [20, 21].

This a priori community structure was specified to enable the estimation of bridge centrality indices and to facilitate the interpretation of cross-domain associations between family management and psychosocial resources.

2.5 Missing data handling

Missing data were handled differently according to variable type. For general sociodemographic and clinical variables with a small amount of missing data, multiple imputation was performed. However, imputation was not applied to the 12 network node variables. This decision was made because the *Parental Mutuality* dimension was structurally inapplicable to caregivers without a spouse, rather than being missing at random, and because the network analysis required complete data across all predefined nodes. Therefore, all network estimation, centrality analyses, and robustness analyses were conducted using the complete-case sample of 195 participants.

2.6 Statistical analysis

All analyses were conducted using Python (version 3.10.0) with the pandas, NumPy, SciPy, scikit-learn, NetworkX, and matplotlib packages. Descriptive statistics were first calculated for participant characteristics and node variables. Continuous variables were summarized as mean ± standard deviation or median with interquartile range, as appropriate, and categorical variables were summarized as counts and percentages.

No universally accepted a priori power analysis exists for Graphical LASSO network models. Simulation-based recommendations indicate that, for a 12-node network, a sample of approximately 150–200 participants is typically required for stable centrality estimation [15, 26]. The present sample of 195 participants falls within this range, and the obtained CS-coefficient of 0.50 for both Strength and Bridge Strength (see Results) meets the recommended stability threshold [15].

For the network analysis, the 12 node variables were standardized before model estimation. A Gaussian graphical model was estimated using the graphical least absolute shrinkage and selection operator (Graphical LASSO) with cross-validation to select the optimal regularization parameter. The resulting network represented regularized partial correlations among the 12 nodes, such that each edge reflected the unique association between two nodes after controlling for all other nodes in the network.

Node importance was quantified using Strength and Expected Influence. Strength was defined as the sum of the absolute edge weights connected to a node, whereas Expected Influence was defined as the sum of signed edge weights connected to a node. To identify nodes that linked different conceptual communities, Bridge Strength was calculated as the sum of the absolute edge weights connecting a node to nodes in other communities.

Edge robustness was evaluated using nonparametric bootstrap analysis with 500 resamples. Bootstrap 95% confidence intervals were calculated for edge weights, and edges with confidence intervals not crossing zero were considered relatively robust. The stability of centrality indices was assessed using case-dropping bootstrap analysis with 500 iterations. Stability was quantified by examining the correlation between centrality estimates derived from the original sample and those derived from subsamples with increasing proportions of cases removed. The correlation stability coefficient (CS-coefficient) was used to evaluate robustness, with values ≥ 0.25 considered acceptable and values ≥ 0.50 considered good.

In the primary analysis, the network was estimated using standardized observed scores. As a sensitivity analysis, rank-based inverse normal transformation was applied to the

node variables and the network was re-estimated to assess the consistency of centrality results. The network was visualized with node colors representing community membership, edge colors indicating the direction of association, edge thickness proportional to the magnitude of the partial correlation, and node size proportional to Strength centrality.

2.7 Ethical considerations

This study was approved by the Ethics Committee of Shenzhen Second People's Hospital (approval number: [2025-45I-02PJ]). Written informed consent was obtained from all participants prior to data collection. All procedures were conducted in accordance with relevant ethical standards and regulations.

3. Results

3.1 Participant characteristics

A total of 195 participants were included in the analysis. The median age of the children was 11.0 years (Q1–Q3, 9.0–14.0), and the median body mass index was 16.6 kg/m² (Q1–Q3, 15.5–18.8). The mean age of fathers and mothers was 41.0 ± 6.2 years and 38.5 ± 5.9 years, respectively. The median number of minor children in the household was 2.0 (Q1–Q3, 1.0–2.0). The median pre-transfusion hemoglobin level at the most recent transfusion was 92.0 g/L (Q1–Q3, 86.0–98.5), and the median age at first iron chelation was 3.0 years (Q1–Q3, 2.0–5.0) (Table 1).

Of the 195 children, 117 (60.0%) were male and 78 (40.0%) were female. Most were not only children (89.2%). Junior high school was the most common educational level among both fathers (59.5%) and mothers (52.3%). Regarding employment status, 52.3% of fathers were full-time employed, whereas mothers were distributed across full-time employment (28.2%), part-time employment (31.8%), and unemployment (33.8%) (Table 1).

3.2 Descriptive statistics of network nodes

Descriptive statistics for the 12 network nodes are presented in Table 2. Among the family management dimensions, FM: Family Life Difficulty had the highest mean score (45.5 ± 8.7), followed by FM: Management Ability (42.6 ± 5.2) and FM: Condition-Related Worry (33.1 ± 4.5). FM: Management Burden had the lowest mean score among the family management dimensions (15.2 ± 3.0). Among psychosocial resource variables, Family Intimacy had the highest mean score (55.7 ± 10.7), whereas Disease Knowledge had the lowest mean score (25.0 ± 2.1) (Table 2).

3.3 Network structure

The estimated network is shown in Fig. 1. The network included both within-community and between-community connections. Positive edges were observed within the psychosocial resource community and within the burden-related family management community. Negative edges were mainly observed between adaptation-related and burden-related family management dimensions, as well as between family management and psychosocial resource variables (Fig. 1).

As shown in Table 4, the strongest positive edge was between SS: Friends and SS: Others (partial correlation = 0.470, 95% CI 0.330 to 0.584), followed by the edges between Family Intimacy and SS: Family (0.410, 95% CI 0.290 to 0.511), FM: Family Life Difficulty and FM: Management Burden (0.407, 95% CI 0.276 to 0.508), and FM: Condition-Related Worry and FM: Family Life Difficulty (0.371, 95% CI 0.250 to 0.468). The strongest negative edge was between FM: Child Daily Life and FM: Family Life Difficulty (-0.331, 95% CI -0.440 to -0.199) (Table 4; Fig. 4).

3.4 Centrality and bridge centrality

Centrality and bridge centrality indices are reported in Table 3 and illustrated in Fig. 2. FM: Family Life Difficulty showed the highest Strength centrality (1.491), followed by SS: Family (1.192), SS: Friends (1.177), and Family Intimacy (1.157). Disease Knowledge had the lowest Strength value (0.581) (Table 3; Fig. 2A).

For Expected Influence, the highest values were observed for SS: Family (1.050), SS: Others (0.996), Parenting Self-Efficacy (0.940), and Family Intimacy (0.927). FM: Child Daily Life had a slightly negative Expected Influence (-0.091) (Table 3).

Bridge centrality analysis identified FM: Parental Mutuality as the node with the highest Bridge Strength (0.922), followed by FM: Family Life Difficulty (0.713), FM: Management Ability (0.601), and FM: Child Daily Life (0.553) (Table 3; Fig. 2B).

3.5 Robust edges

Edges with bootstrap 95% confidence intervals not crossing zero are shown in Table 4 and Fig. 4. Within-community robust edges included SS: Friends–SS: Others, Family Intimacy–SS: Family, FM: Family Life Difficulty–FM: Management Burden, and FM: Condition-Related Worry–FM: Family Life Difficulty. Additional robust edges within the psychosocial resource community were observed for SS: Family–SS: Others, SS: Family–SS: Friends, and Parenting Self-Efficacy–Family Intimacy (Table 4; Fig. 4).

Several robust between-community edges were also identified. FM: Parental Mutuality was positively associated with Family Intimacy (0.276, 95% CI 0.146 to 0.404) and SS: Family (0.160, 95% CI 0.045 to 0.272), and negatively associated with FM: Family Life Difficulty (-0.187, 95% CI -0.288 to -0.080). FM: Management Ability was

positively associated with Parenting Self-Efficacy (0.167, 95% CI 0.015 to 0.294) and negatively associated with FM: Family Life Difficulty (-0.118, 95% CI -0.225 to -0.001). FM: Condition-Related Worry was negatively associated with SS: Friends (-0.119, 95% CI -0.216 to -0.002) (Table 4; Fig. 4).

3.6 Stability of centrality estimates

The stability of centrality estimates was assessed using case-dropping bootstrap analysis (Table 5; Fig. 3). As the proportion of dropped cases increased from 10% to 60%, the mean correlation for Strength ranged from 0.985 to 0.804, and the probability of retaining a correlation of at least 0.70 ranged from 1.000 to 0.864. For Bridge Strength, the mean correlation ranged from 0.988 to 0.852, and the corresponding probability ranged from 1.000 to 0.948 (Table 5).

The CS-coefficient was 0.50 for both Strength and Bridge Strength. As shown in Fig. 3, both indices remained relatively stable across increasing levels of case removal, supporting the stability of the centrality estimates.

4. Discussion

To date, no study has simultaneously mapped the internal structure of family management dimensions and their connections with psychosocial resources in TDT families using network analysis, leaving the bridge architecture linking these two domains entirely uncharacterized. Conventional regression-based approaches estimate each pairwise association while adjusting for a fixed set of covariates, but they cannot isolate the unique partial correlation between any two variables after controlling for all other family management and psychosocial variables concurrently. Network analysis with a Gaussian graphical model overcomes this limitation by estimating a sparse partial correlation network in which each retained edge represents an association that persists after conditioning on every other node in the system. Moreover, bridge centrality—a metric without a direct analogue in regression or structural equation modeling—quantifies the extent to which a node connects two conceptually distinct communities (e.g., family management versus psychosocial resources). A node with high bridge strength is hypothesized to serve as a cross-domain conduit, making it a theoretically prioritized target for interventions aiming to produce spillover effects across domains. Consequently, clinicians and intervention designers currently lack an evidence-based rationale for selecting which family-level variables to prioritize.

This study applies network analysis to construct a partial correlation network of the six FaMM dimensions and six psychosocial resource variables... we aim to: (1) delineate the overall network structure and edge patterns among family management dimensions and psychosocial resources; (2) identify the most influential (high-centrality) and bridge nodes linking family management and psychosocial resources—an analytic objective unattainable through regression-based approaches alone; and (3) generate network-informed hypotheses regarding high-priority targets for family-centered

interventions, with particular attention to nodes exhibiting high bridge centrality as candidate leverage points for cross-domain intervention effects.

Consistent with descriptive statistics indicating that Family Life Difficulty yielded the highest mean score (45.5 ± 8.7), this dimension emerged as the most influential hub node (Strength = 1.491). Its high centrality indicates its pervasive role as a systemic stressor that affects and shapes nearly all facets of family management and psychosocial adaptation among TDT families. The positive partial correlations between Family Life Difficulty and both Management Burden (r = 0.407) and Condition-Related Worry (r = 0.371) demonstrate that disruptions to daily family life exacerbate caregiving burden and disease-specific anxiety, thereby forming a self-reinforcing stress cycle. Conversely, its robust negative association with Child Daily Life (r = −0.331) shows a zero-sum dynamic: efforts to sustain the child's daily routine are directly undermined by TDT-related time commitments, travel burdens, and financial constraints. This network topology identifies Family Life Difficulty as a primary intervention target, wherein its modulation is anticipated to elicit potential targets for intervention across multiple family management domains— a key advantage of network-informed intervention design.

Notably, Parental Mutuality was identified as the predominant bridge node (Bridge Strength = 0.922), linking the Family Management community to the Psychosocial Resources community. As conceptualized by shared decision-making, emotional collaboration, and collaborative caregiving[22-25], Parental Mutuality functions as a "connective catalyst" that bridges adaptive family management to psychosocial resources, including family intimacy and social support. Its positive associations with Family Intimacy (r = 0.276) and Family Social Support (r = 0.160), coupled with its negative association with Family Life Difficulty (r = −0.187), confirm that spousal collaboration mitigates systemic stress and enhances adaptive family functioning. This finding is particularly notable within the context of our sample, wherein 89.2% of children were from multi-child households and 33.8% of mothers were unemployed. Within these resource-constrained settings, spousal collaboration constitutes not merely a relational asset but a functional prerequisite for sustaining consistent TDT care.

Within the Psychosocial Resources community, our findings demonstrate that psychosocial resources function as an interconnected system rather than discrete factors. Robust positive edges between Social Support from Friends and Social Support from Others (r = 0.470), as well as between Family Intimacy and Family Social Support (r = 0.410), demonstrate the synergistic nature of psychosocial resilience among caregivers of children with chronic diseases. Parenting Self-Efficacy also demonstrated meaningful cross-community associations with Management Ability (r = 0.167), reinforcing the notion that self-efficacy acts as a foundational resource for effective chronic disease management. In contrast, Disease Knowledge exhibited the lowest centrality (Strength = 0.581) and lacked robust cross-community edges, indicating that current levels of disease knowledge—while necessary—are insufficient to meaningfully alter family management outcomes or mitigate caregiving burdens within the broader network system. This observation aligns with recent TDT-focused educational research, which demonstrates that standalone knowledge-based

interventions yield limited impact in the absence of concurrent psychosocial support [26, 27].

4.1 Comparison with Prior Literature

Our findings extend and refine the existing literature on TDT and family management in pediatric chronic diseases across three key dimensions. First, prior studies have documented elevated caregiving burden and compromised family functioning among TDT families[28, 29]; however, conventional regression-based approaches are unable to capture the concurrent, interdependent relationships among multiple family-level variables. Through the application of network analysis, we identified hub and bridge nodes that delineate how family management and psychosocial resources interact as an integrated system[30]. For instance, the robust positive association between Management Burden and Family Life Difficulty constitutes a tightly coupled cluster—a dynamic only observable through network estimation[31].

Second, our validation of the Family Management Measure (FaMM) in a Chinese TDT sample aligns with cross-cultural FaMM research conducted in pediatric cancer[25] and asthma [32]populations. Nevertheless, our study advances this body of literature by demonstrating that Family Life Difficulty is more central among TDT families than in families affected by other chronic conditions. This population-specific discrepancy reflectss the unique lifelong, recurrent, and resource-intensive nature of TDT care— a characteristic distinct from the episodic burdens associated with conditions such as asthma or cancer[33, 34].

Third, the identification of Parental Mutuality as a bridge node supports family systems theory [35] and aligns with prior findings in Down syndrome and childhood cancerpopulations. By quantifying its bridge strength within a TDT-specific context and linking it to objective psychosocial metrics, our study clarifiess the mechanistic pathway through which spousal collaboration shapes adaptive family functioning— a critical advancement beyond correlational and qualitative studies[36, 37].

The low centrality of Disease Knowledge stands in contrast to studies that conceptualize knowledge as a key modifiable target [29]. This discrepancy stems from the fact that prior research evaluated knowledge in isolation, whereas network analysis accounts for confounding factors from all other variables in the system. Our findings indicate that knowledge acquisition alone is insufficient to reduce caregiving burden or improve family management, unless paired with enhanced psychosocial support and family collaboration— insights supported by intervention trials demonstrating that integrated psychosocial education yields superior outcomes compared to standalone knowledge-based training[26, 27].

4.2 Theoretical and Clinical Implications

4.2.1 Theoretical Contributions

This study makes two distinct theoretical contributions. First, it validates the FaMM framework[9, 13] among Chinese TDT populations and extends it to a network-based

systems perspective. Instead of modeling family adaptation as linear pathways, we propose a dynamic network model that emphasizes interdependencies, hub nodes, and bridge nodes— one that more accurately captures the complex, reciprocal nature of lifelong pediatric care[36].

Second, it expands the application of network science to family management research in pediatrics. Most pediatric network studies have centered on psychopathological symptoms[25] , with few investigating family management or psychosocial resources. Our robust CS coefficient (0.50) offers methodological guidance for future network studies on family adaptation in chronic diseases, encompassing sample size planning and bootstrap validation procedures. Additionally, the identification of community clusters and bridge nodes provides a transferable conceptual framework for future network studies on family adaptation in other lifelong conditions, such as sickle cell disease and cystic fibrosis[33, 37].

4.2.2 Clinical Implications

The strong centrality of Family Life Difficulty and the prominent bridge role of Parental Mutuality observed in the network suggest that these two nodes are promising intervention targets for improving family functioning in Chinese TDT families; however, their causal therapeutic effects remain to be verified by randomized controlled trials (RCTs). Considering the unique context of multi-child households, maternal unemployment, and low educational attainment in southern China[27], interventions targeting this node would preferably address the structural determinants of family life difficulty.

First, potential intervention strategies targeting Family Life Difficulty include: (1) integrated care coordination to streamline transfusion and iron chelation therapy schedules and minimize healthcare visit burdens; (2) financial and employment advocacy initiatives to support caregivers, particularly mothers; and (3) practical logistical support to assist families in balancing TDT care with sibling care responsibilities and daily routines. Such interventions may reduce caregiving burden, disease-related worry, and disruptions to the child's daily functioning.

Second, interventions aimed at enhancing Parental Mutuality as a candidate bridge target may include: (1) dyadic training for shared TDT care management; (2) peer support groups tailored for caregiver couples; and (3) family therapy that fosters collaboration within extended family networks— a structure common in Chinese culture[35]. By fostering spousal collaboration, interventions can connect adaptive family management to the activation of psychosocial resources, generating a synergistic effect across the family system.

Additional preliminary clinical suggestions derived from the network findings include integrating knowledge-based education with psychosocial support; capitalizing on the interconnectedness of psychosocial resources; and adapting all interventions to meet the needs of low-literacy caregivers[23, 31, 32].

4.3 Study Limitations

The present study is subject to several limitations. First, the cross-sectional study design precludes causal inference, necessitating longitudinal research to elucidate directional effects[26]. Second, the use of convenience sampling from a single clinical center may restrict the generalizability of findings to other geographic regions or low- and middle-income country (LMIC) settings[22]. Third, the Parental Mutuality dimension is not applicable to single caregivers, a population that encounters unique challenges[34]. Fourth, other family members, such as grandparents and siblings, were not incorporated into the study, despite their pivotal role in TDT care[27]. Fifth, objective clinical outcomes— including treatment adherence and serum ferritin levels— were not assessed, which limits our understanding of how the family network influences child health outcomes[24].Finally, the CS-coefficient of 0.50 for centrality and bridge strength estimates, while meeting the recommended threshold [15], represents the lower bound of acceptable stability and should be interpreted with caution.

4.4 Future Research Directions

Future research endeavors should: (1) conduct prospective longitudinal studies to map temporal dynamics of the network; (2) replicate the findings in multicenter Chinese samples and across diverse cultural contexts; (3) incorporate single caregivers and extended family members into study designs; (4) test targeted interventions through randomized controlled trials (RCTs); (5) integrate objective clinical variables into the network model; and (6) develop machine learning models to identify families at high risk of poor family functioning [25, 35].

5. Conclusions

This study constructed the first network of family management dimensions and psychosocial resources in Chinese families of children with transfusion-dependent beta-thalassemia (TDT). The network identified Family Life Difficulty as the central hub node and Parental Mutuality as the primary bridge node linking family management and psychosocial resources, with both centrality and bridge strength estimates demonstrating good stability (CS-coefficient = 0.50). These findings extend the family management literature by demonstrating that family adaptation to TDT operates as an interconnected system rather than a set of independent variables. The central position of Family Life Difficulty suggests that disruptions to family daily life constitute a core systemic stressor that propagates across multiple domains of family functioning. The bridge role of Parental Mutuality further indicates that spousal collaboration may serve as a critical cross-domain pathway through which psychosocial resources translate into better family management outcomes.

These findings have practical implications for family-centered care in pediatric TDT. First, assessment and support should prioritize reducing family life disruption, particularly for multi-child households and families with unemployed mothers. Second, interventions that strengthen spousal collaboration may have broader downstream benefits than single-domain support programs. Longitudinal and interventional

research is needed to confirm the causal direction of these associations and to evaluate the effectiveness of network-informed intervention strategies.

Abbreviations

TDT: Transfusion-dependent beta-thalassemia; HSCT: Hematopoietic stem cell transplantation; FaMM: Family Management Measure; GGM: Gaussian graphical model; LASSO: Least Absolute Shrinkage and Selection Operator; CS: Correlation stability; CI: Confidence interval; EI: Expected Influence; SD: Standard deviation; Q1: First quartile; Q3: Third quartile; BMI: Body mass index; LMIC: Low- and middle-income countries; RCT: Randomized controlled trial; FM: Family management; SS: Social support.

Table 1. Characteristics of the study participants

Variable	Level	Summary / n (%)
Child age, years	—	11.0 (9.0, 14.0)
Body mass index, kg/m²	—	16.6 (15.5, 18.8)
Father age, years	—	41.0 ± 6.2
Mother age, years	—	38.5 ± 5.9
Number of minor children in the household	—	2.0 (1.0, 2.0)
Pre-transfusion hemoglobin at the most recent transfusion, g/L	—	92.0 (86.0, 98.5)
Age at first iron chelation, years	—	3.0 (2.0, 5.0)
Child sex	Male	117 (60.0)
	Female	78 (40.0)
Only child	No	174 (89.2)
	Yes	21 (10.8)
Father education level	Primary school or below	10 (5.1)

Variable	Level	Summary / n (%)
	Junior high school	116 (59.5)
	Senior high school/technical secondary school	48 (24.6)
	Junior college	13 (6.7)
	Bachelor's degree	8 (4.1)
Mother education level	Primary school or below	17 (8.7)
	Junior high school	102 (52.3)
	Senior high school/technical secondary school	46 (23.6)
	Junior college	25 (12.8)
	Bachelor's degree	5 (2.6)
Father employment status	Full-time employed	102 (52.3)
	Part-time employed	48 (24.6)
	Unemployed	24 (12.3)
	Other	21 (10.8)
Mother employment status	Full-time employed	55 (28.2)
	Part-time employed	62 (31.8)
	Unemployed	66 (33.8)
	Other	12 (6.2)

Note. Continuous variables are presented as mean ± standard deviation or median (Q1, Q3), as appropriate. Categorical variables are presented as n (%). Q1 = first quartile; Q3 = third quartile.

Table 2. Descriptive statistics for network nodes

Node	Mean ± SD	Median (Q1, Q3)
FM: Child Daily Life	17.6 ± 3.8	18.0 (15.0, 20.0)
FM: Management Ability	42.6 ± 5.2	42.0 (39.0, 47.0)
FM: Parental Mutuality	31.0 ± 6.0	32.0 (28.0, 35.0)
FM: Condition-Related Worry	33.1 ± 4.5	33.0 (30.0, 36.0)
FM: Family Life Difficulty	45.5 ± 8.7	47.0 (40.0, 51.0)
FM: Management Burden	15.2 ± 3.0	15.0 (14.0, 17.0)
Disease Knowledge	25.0 ± 2.1	25.0 (24.0, 26.5)
Parenting Self-Efficacy	35.1 ± 6.1	36.0 (32.5, 40.0)
Family Intimacy	55.7 ± 10.7	57.0 (48.5, 62.0)
SS: Family	19.7 ± 4.9	20.0 (16.0, 23.5)
SS: Friends	17.0 ± 5.1	17.0 (14.0, 20.0)
SS: Others	17.5 ± 4.6	17.0 (14.5, 20.0)

Note. FM = family management; SS = social support; SD = standard deviation; Q1 = first quartile; Q3 = third quartile.

Table 3. Centrality and bridge centrality indices of network nodes

Node	Strength	Expected Influence	Bridge Strength	Community
FM: Family Life Difficulty	1.491	0.212	0.713	FM–Burden
SS: Family	1.192	1.050	0.163	Psychosocial Resources
SS: Friends	1.177	0.572	0.273	Psychosocial Resources
Family Intimacy	1.157	0.927	0.418	Psychosocial Resources
FM: Parental Mutuality	1.082	0.516	0.922	FM–Adaptation
SS: Others	1.081	0.996	0.155	Psychosocial Resources
Parenting Self-Efficacy	1.018	0.940	0.403	Psychosocial Resources
FM: Child Daily Life	0.895	-0.091	0.553	FM–Adaptation
FM: Management Ability	0.830	0.459	0.601	FM–Adaptation
FM: Management Burden	0.750	0.435	0.252	FM–Burden
FM: Condition-Related Worry	0.725	0.275	0.264	FM–Burden
Disease Knowledge	0.581	0.445	0.288	Psychosocial Resources

Note. Nodes are ordered by Strength in descending order. Higher Strength values indicate greater overall connectedness within the network, whereas higher Bridge Strength values indicate stronger connections to nodes in other communities. FM = family management.

Table 4. Network edges with non-zero bootstrap 95% confidence intervals

Node 1	Node 2	Original partial correlation	95% bootstrap CI	Same community
SS: Friends	SS: Others	0.470	[0.330, 0.584]	Yes
Family Intimacy	SS: Family	0.410	[0.290, 0.511]	Yes
FM: Family Life Difficulty	FM: Management Burden	0.407	[0.276, 0.508]	Yes
FM: Condition-Related Worry	FM: Family Life Difficulty	0.371	[0.250, 0.468]	Yes
FM: Child Daily Life	FM: Family Life Difficulty	-0.331	[-0.440, -0.199]	No
SS: Family	SS: Others	0.283	[0.154, 0.404]	Yes
FM: Parental Mutuality	Family Intimacy	0.276	[0.146, 0.404]	No
SS: Family	SS: Friends	0.213	[0.086, 0.342]	Yes
Parenting Self-Efficacy	Family Intimacy	0.212	[0.093, 0.311]	Yes
FM: Child Daily Life	FM: Management Ability	0.206	[0.080, 0.318]	Yes
FM: Parental Mutuality	FM: Family Life Difficulty	-0.187	[-0.288, -0.080]	No
FM: Management Ability	Parenting Self-Efficacy	0.167	[0.015, 0.294]	No
FM: Parental Mutuality	SS: Family	0.160	[0.045, 0.272]	No
Parenting Self-Efficacy	SS: Friends	0.147	[0.046, 0.243]	Yes
FM: Child Daily Life	FM: Parental Mutuality	0.136	[0.012, 0.252]	Yes

Node 1	Node 2	Original partial correlation	95% bootstrap CI	Same community
FM: Condition-Related Worry	SS: Friends	-0.119	[-0.216, -0.002]	No
FM: Management Ability	FM: Family Life Difficulty	-0.118	[-0.225, -0.001]	No

Note. Only edges with bootstrap 95% confidence intervals not crossing zero are presented. Positive values indicate positive partial correlations, whereas negative values indicate negative partial correlations. CI = confidence interval.

Table 5. Case-dropping bootstrap stability of centrality indices

Drop proportion	Retained proportion	Mean r (Strength)	P[r ≥ 0.70] for Strength	Mean r (Bridge Strength)	P[r ≥ 0.70] for Bridge Strength
10%	90%	0.985	1.000	0.988	1.000
20%	80%	0.965	1.000	0.973	1.000
30%	70%	0.944	1.000	0.955	1.000
40%	60%	0.911	1.000	0.928	1.000
50%	50%	0.865	0.976	0.894	0.996
60%	40%	0.804	0.864	0.852	0.948

Note. Mean r represents the average correlation between centrality indices estimated from the full sample and those estimated from subsamples after case dropping. The correlation stability coefficient (CS-coefficient) was 0.50 for both Strength and Bridge Strength, indicating good stability.

Figure legend

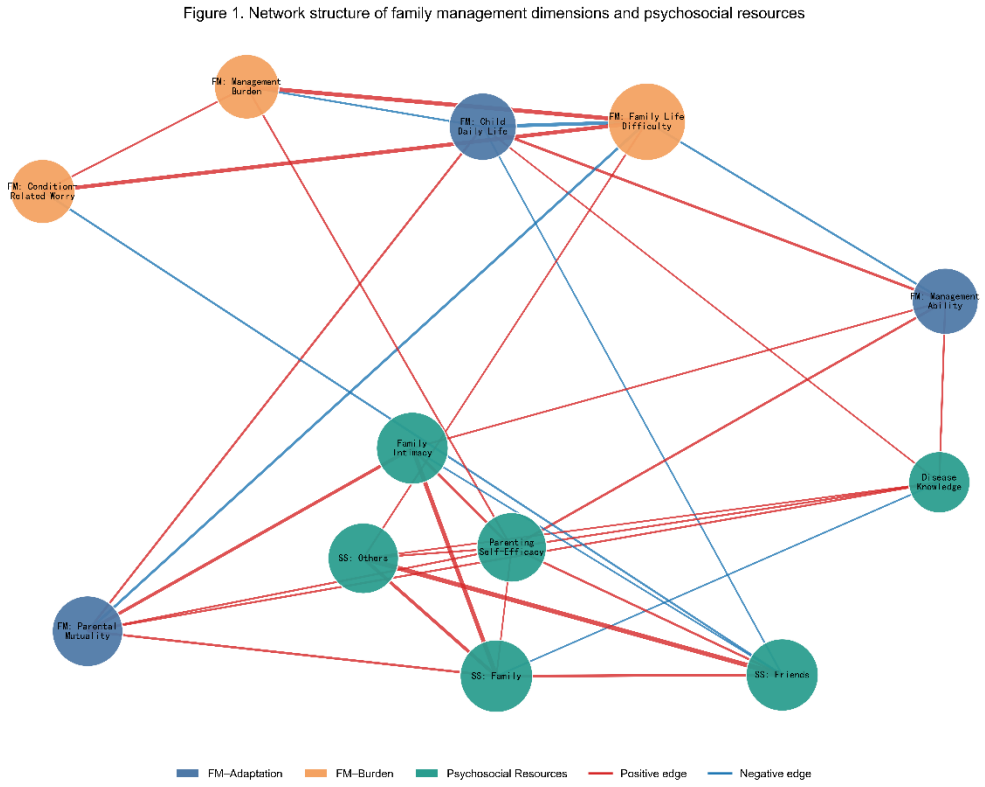


Figure 1. Estimated network structure of family management dimensions and psychosocial resources. Nodes represent the 12 study variables, and edges represent regularized partial correlations between nodes after controlling for all other variables in the network. Red edges indicate positive associations, whereas blue edges indicate negative associations. Edge thickness is proportional to the magnitude of the partial correlation. Node colors indicate community membership, including FM–Adaptation, FM–Burden, and Psychosocial Resources. Larger nodes indicate higher Strength centrality.

Figure 2. Centrality indices of the network

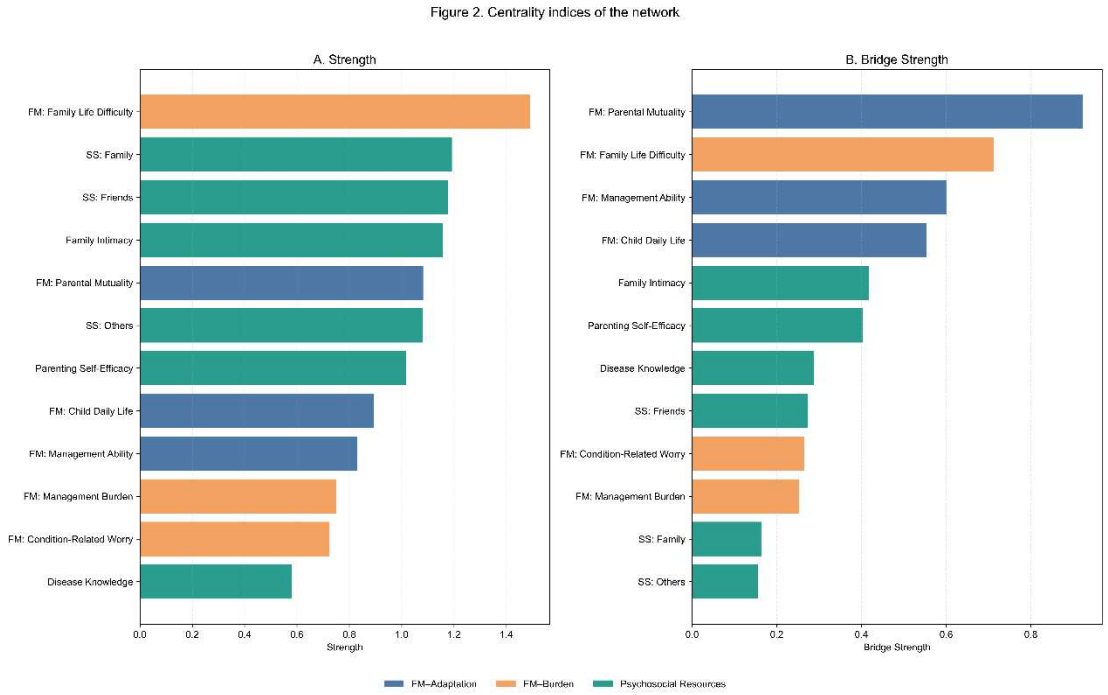


Figure 2. Centrality indices of the estimated network. Panel A displays Strength centrality, reflecting the overall connectedness of each node within the network. Panel B displays Bridge Strength, reflecting the extent to which each node connects with nodes from other communities. Bars are ordered from highest to lowest centrality. Colors indicate community membership: FM–Adaptation, FM–Burden, and Psychosocial Resources.

Figure 3. Case-dropping bootstrap stability of centrality indices

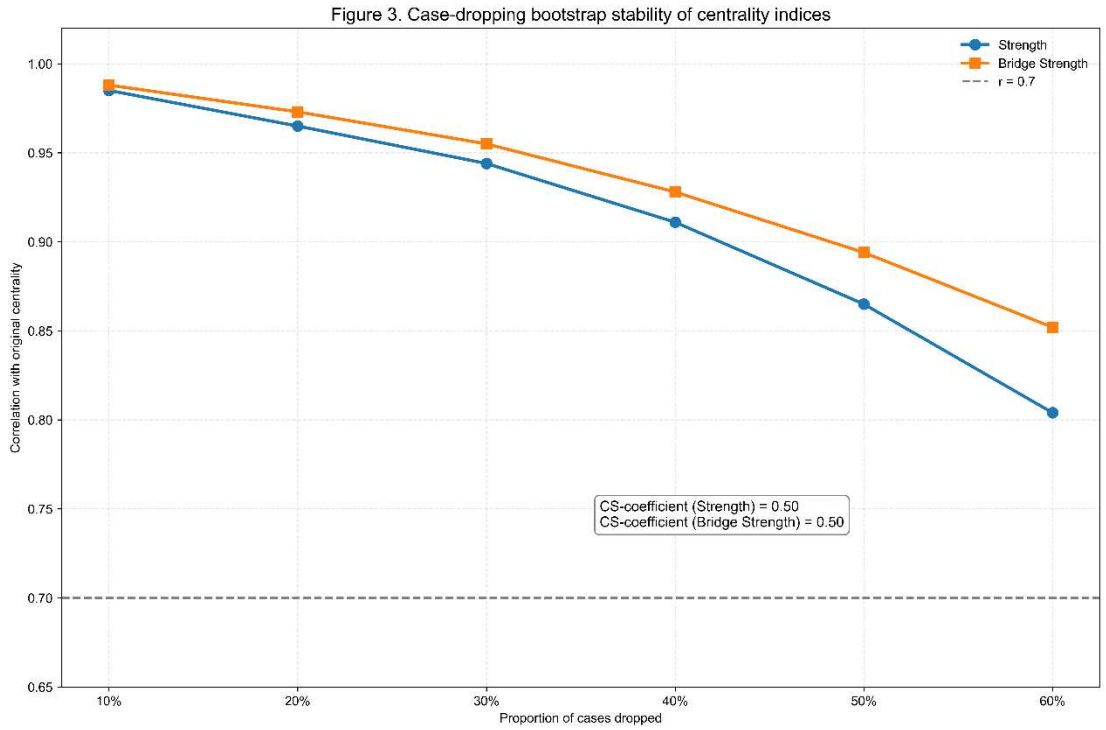


Figure 3. Case-dropping bootstrap results for the stability of centrality indices. The y-axis represents the correlation between centrality values estimated from the full sample and those estimated from subsamples after dropping increasing proportions of cases. The dashed horizontal line indicates the reference threshold of r = 0.70. The estimated correlation stability coefficient (CS-coefficient) was 0.50 for both Strength and Bridge Strength, indicating good stability of the centrality estimates.

Figure 4. Bootstrap 95% confidence intervals of robust edge weights.

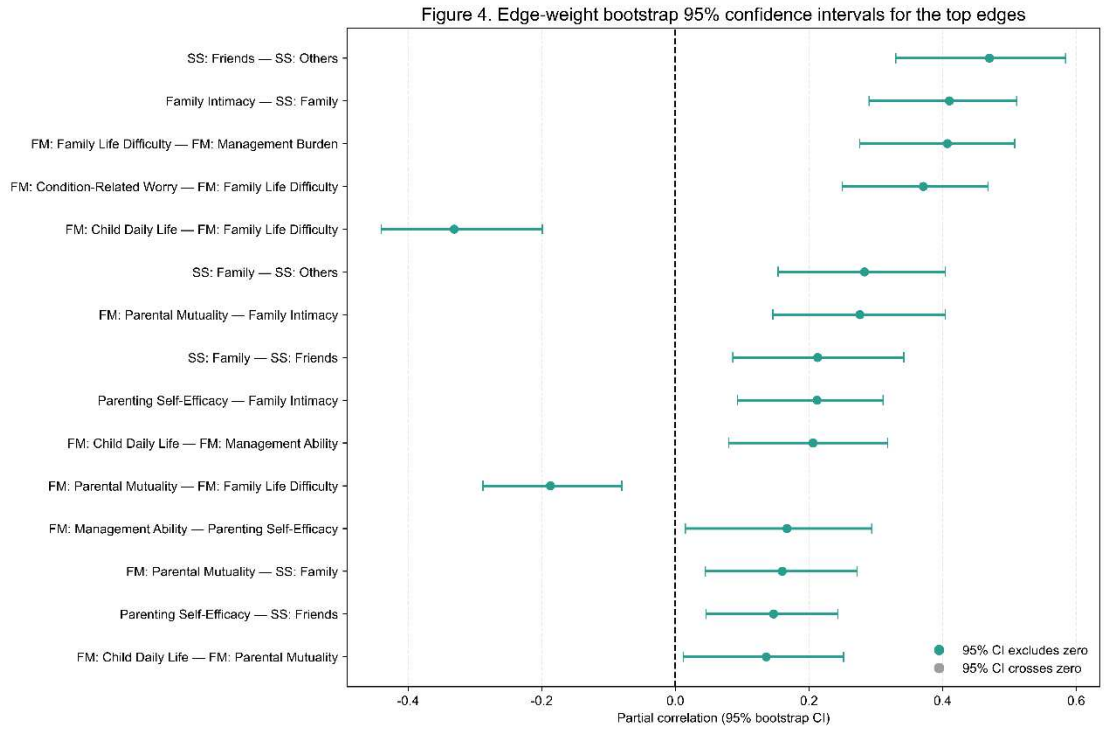


Figure 4. Bootstrap 95% confidence intervals for robust edge weights in the estimated network. Points represent the original partial correlation coefficients, and horizontal lines represent the corresponding 95% bootstrap confidence intervals. The vertical dashed line indicates zero. Only edges with 95% bootstrap confidence intervals not crossing zero are displayed, indicating relatively robust associations.

Declarations

Ethics approval and consent to participate

This study was approved by the Ethics Committee of Shenzhen Second People's Hospital (approval number: [2025-45I-02PJ]). Written informed consent was obtained from all participants prior to data collection. All procedures were conducted in accordance with the Declaration of Helsinki.

Consent for publication

Not applicable. This manuscript does not contain any individual person's data in any form.

Availability of data and materials

The datasets generated and analyzed during the current study are not publicly available due to privacy restrictions but are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

XX and HX: Conceptualization, Methodology, Investigation, Writing — Original Draft. LZ: Data curation, Formal analysis. JY: Investigation, Visualization. LM: Investigation, Data curation. FH: Investigation, Formal analysis. SS: Supervision, Writing — Review & Editing, Project administration. JL: Conceptualization, Supervision, Writing — Review & Editing, Funding acquisition. All authors reviewed and approved the final

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