

Original Article

Effects of low-intensity exercise combined with digital health education on continuous care for maintenance hemodialysis patients

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Abstract: Objective: To evaluate and compare the efficacy of digital health education (DHE), low-intensity exercise (LIT), and their combination in maintenance hemodialysis (MHD) patients. Methods: A total of 200 MHD patients treated at Zhejiang Provincial Tongde Hospital from August to October 2025 were randomly assigned to four groups (n=50 per group): the control group (standard care), DHE group, LIT group, and DHE+LIT group. The Interventions lasted 24 weeks. Assessments included cardiopulmonary function parameters (anaerobic threshold [AT], peak oxygen uptake [peak VO₂], and 6-minute walk test [6MWT]), the Short Form-36 Health Survey (SF-36), self-management ability, Self-Rating Depression Scale (SDS), Subjective Global Assessment (SGA) nutritional status, serum albumin, prealbumin, high-sensitivity C-reactive protein (hs-CRP), myostatin, adverse events, and patient satisfaction. Results: After 24 weeks of intervention, AT and 6MWT significantly improved in all three intervention groups compared with the control group (all P<0.05), with the combination group demonstrating greater improvements than either single-intervention group (both P<0.05). No significant differences in peak VO₂ were observed among the four groups (P>0.05). Compared with the single-intervention groups, the combination group showed significantly better improvements in general health, vitality, mental health, and all self-management dimensions (all P<0.05). DHE alone resulted in greater improvements health knowledge and social functioning than LIT alone, whereas LIT alone provided greater improvements in self-care skills and bodily pain than DHE alone (all P<0.05). All three intervention groups showed significant within-group improvements in SDS and SGA (all P<0.05), and the combination group achieved the lowest SDS and highest SGA compared with either single-intervention group (both P<0.05). Serum albumin and prealbumin levels increased, whereas hs-CRP and myostatin levels decreased in all intervention groups, with the combination group showing the most pronounced changes (all P<0.05). The incidence rates of adverse event rates were 22.0%, 12.0%, 10.0%, and 6.0% in the control, DHE, LIT, and combination groups, respectively, while patient satisfaction rates were 82.0%, 88.0%, 90.0%, and 96.0%, respectively. However, between-group differences did not reach statistical significance for either outcome. Conclusion: The integration of digital health education with low-intensity exercise may represent a promising adjunctive nursing strategy for MHD patients, with potential benefits in improving exercise tolerance, self-management ability, and quality of life. Further multicenter studies with longer follow-up are warranted to validate these findings and evaluate long-term clinical outcomes.

Keywords: Low-intensity exercise, maintenance hemodialysis, digital health education, nursing, cardiopulmonary function

Introduction

Maintenance hemodialysis (MHD) remains the standard renal replacement therapy for patients with end-stage renal disease, substantially prolonging survival; however, its limitations should not be overlooked [1, 2]. Although dialysis therapy is capable of clearing toxins, it cannot completely restore normal physiological functions and is frequently associated with

complications (e.g., sarcopenia, cardiovascular disease) that markedly impair exercise tolerance and quality of life (QoL) [3]. In addition, MHD patients often face strict dietary restrictions and reduced appetite, potentially resulting in malnutrition thus further limiting their participation in rehabilitation activities [4].

Currently, continuous care is one of the commonly used and effective nursing strategies for

MHD patients. This approach extends in-hospital care to the out-of-hospital setting, enabling patients to receive professional nursing guidance after discharge [5]. Traditional continuous care primarily relies on approaches such as telephone communication, home visits, and outpatient consultations. However, these methods have several limitations. For example, telephone follow-ups lack direct visual interaction, whereas home visits may be constrained by considerable time and resource requirements [6]. Thus, traditional continuous care models have not fully satisfied the evolving needs of MHD patients.

In recent years, mobile health technology has been increasingly applied in healthcare. According to the World Health Organization, mobile health technology refers to the use of mobile devices, including cell phones, patient monitoring devices, personal digital assistants (PDAs), and other wireless intelligent terminals, to support medical and public health practices [7]. These technologies facilitate remote monitoring and consultation while enabling the delivery of personalized health management plans, thereby improving the continuity and coordination of nursing services [8]. Furthermore, accumulating evidence indicates that low-intensity exercise, as an established physical intervention, provides beneficial effects in MHD patients, including improvements in cardiorespiratory performance, dialytic clearance, mineral metabolism, psychosocial function, and nutritional indices, as well as reductions in anxiety and depressive symptoms [9, 10].

Therefore, this study was designed as a four-arm parallel randomized trial to address two critical questions: (i) whether digital health education (DHE) and low-intensity exercise (LIE) each independently provide clinical benefits, and (ii) whether their combination yields synergistic effects beyond either intervention alone. By comparing standard care against DHE alone, LIE alone, and combined DHE+LIE over a 24-week period, we aimed to clarify the independent and combined effects of these interventions and provide evidence for optimizing rehabilitation nursing strategies in MHD patients.

Materials and methods

Study design

This interventional study enrolled 200 patients undergoing MHD at Zhejiang Provincial Tongde

Hospital between August and October 2025. Eligible patients were randomly assigned to one of four groups (n=50 per group): the control group (standard continuous care), DHE alone group (standard care + WeChat-based DHE), LIE alone group (standard care + LIE), or combination group (standard care + DHE + LIE). Randomization was performed using a computer-generated block randomization scheme (block size =8), and allocation was concealed using sealed opaque envelopes.

The study protocol was approved by the Ethics Committee of Zhejiang Provincial Tongde Hospital (Approval No. Zhe Tongde Lun Shen 2025 Yan No. 281-JY) and was conducted in compliance with the principles of the Declaration of Helsinki. This trial was registered with the Thai Clinical Trials Registry (TCTR20260623006). All participants provided written informed consent before enrollment.

Sample size calculation

The sample size was calculated based on previous research findings [11]. Considering the primary outcome of changes in the Subjective Global Assessment (SGA) score from baseline to 24 weeks, a prior power analysis using one-way analysis of variance (ANOVA) indicated that a total sample size of 180 patients (45 per group) would provide 90% statistical power to detect a medium effect size ($f=0.25$) with a two-sided α of 0.05. Assuming a 10% dropout rate, the final sample size was increased to 200 patients (50 per group).

Diagnostic criteria

The diagnostic criteria for MHD and end-stage renal disease (ESRD) were based on established clinical guidelines. Diabetes-related chronic kidney disease is primarily defined as a urine albumin/creatinine ratio (UACR ≥ 30 mg/g) and/or an estimated glomerular filtration rate (eGFR) < 15 mL min⁻¹ (1.73 m²)⁻¹ that lasts longer than three months. When other causes of chronic kidney disease are ruled out, diabetic kidney disease is typically diagnosed clinically based on an increase in UACR and/or a decrease in eGFR [12].

Inclusion criteria

(1) Undergoing hemodialysis treatment for more than 3 months with three sessions per week; (2) an expected survival time of more

than 6 months; (3) clear consciousness without cognitive impairment and the ability to use smart devices (e.g., mobile phones); (4) age between 18 and 75 years; (5) absence of severe comorbidities, ability to perform independent mobility, and muscle strength $\geq$ grade 3 according to the Lovett 6-point muscle strength scoring system; (6) ability to walk independently without visual impairment, musculoskeletal injury, or lower limb movement disorders; and (7) willingness to participate in the study and provide written informed consent.

Exclusion criteria

(1) Presence of mobility limitations or inability to complete exercises due to muscle or joint disorders; (2) concomitant central or peripheral nervous system diseases; (3) severe complications, including heart failure, severe infection, or malignant tumors; or (4) withdrawal from the study halfway.

Nursing intervention

Control group: A continuous care team was established, with the head nurse serving as the team leader and coordinating the collaboration among doctors, nurses, and patients. Physicians were responsible for planning and adjusting individualized treatment plans, whereas nurses were responsible for health education during the treatment and follow-up periods, formulation of follow-up plans, and systematic organization and analysis of medical records. The nursing and follow-up interventions include health education covering medication management, exercise guidance, dietary recommendations, and family care. Patients received outpatient follow-up visits every four weeks, and nursing plans were adjusted according to the patient's condition. The intervention period lasted for 24 weeks.

DHE group: A continuous care team was established using the same organizational model that was used in the control group. Prior to the intervention, all team members received standardized training on WeChat platform to ensure the effective delivery of nursing service through the digital platform. Each nurse was assigned a specific number of patients and established a dedicated WeChat patient group. Meanwhile, an official departmental WeChat public account was created, and patients were encouraged to follow the account.

To ensure the standardization and reproducibility of the digital health intervention, a unified standard operating procedure (SOP) was developed as follows:

(1) **Standardized information delivery frequency:** The official WeChat account published three posts per week (on Monday, Wednesday, and Friday at 9:00 a.m.), with each post covering one educational module (Western medicine-related knowledge module twice weekly, and traditional Chinese medicine (TCM) knowledge module once weekly). In the patient WeChat group, responsible nurses sent standardized reminders regarding diet and medication management every morning (8:00-8:30 a.m.) and summarized daily exercise records every evening (20:00-20:30 p.m.).

(2) **Standardized interactive assessment:** A structured interactive assessment form was used ([Supplementary Table 1](#)). Responsible nurses answered patients' questions in the WeChat groups every Tuesday and Thursday, with responses provided within 4 hours. On the first Friday of each month, an online video Q&A session (30 minutes) was conducted jointly by the attending physician and responsible nurse. All sessions were recorded for quality review.

(3) **Quality control of exercise recording:** Patients were required to upload exercise photos or videos to the WeChat group at least three times per week. Responsible nurse reviewed exercise records using a unified quality control checklist, including exercise duration, intensity compliance, and adverse reaction monitoring. Each dimension was scored from 0 to 2 points, resulting in a total score ranging from 0 to 6 points. Patients with scores ≤ 2 received telephone follow-up and additional guidance on the next day. Exercise quality control scores were independently evaluated by two responsible nurses, and only records with an inter-rater consistency Kappa coefficient ≥ 0.80 were included in the analysis.

(4) **Standardized nurse training and implementation monitoring:** Before intervention, four responsible nurses received 8 hours of standardized training, including WeChat platform operation, educational content specification, interactive communication skills, and application of the exercise quality control checklist (2 hours for each component). The post-training assessment pass rate was 100%. During the interven-

tion period, implementation consistency among nurses was evaluated monthly by randomly reviewing 10 records. An intraclass correlation coefficient (ICC) ≥ 0.85 was required to confirm consistency among evaluators.

Content delivery strategy: The official WeChat account group adopted a “Western medicine as the mainstay, TCM as the supplement” strategy. Western medicine education included kidney disease-related knowledge, MHD treatment precautions, dialysis care, and daily management suggestions, including fluid and potassium restriction. TCM-related content was provided once weekly and included health preservation knowledge, exercise-related guidance (e.g., Tai Chi, Ba Duan Jin); emotional regulation approaches (e.g., relaxation techniques and meditation), and dietary recommendations based on syndrome differentiation. All materials were prepared and reviewed by senior physicians and the head nurse to ensure accuracy and practicality. TCM-related components were provided solely as educational content rather than standalone interventions.

WeChat-based activity monitoring: Patients' exercise participation was monitored using exercise function in WeChat. Exercise recommendations were provided, and patients were encouraged to engage in moderate physical activity.

Patient communication and psychological support: Patients were encouraged to share treatment experiences and self-management practices in the WeChat groups, facilitating peer support and enhancing confidence in disease management. Nursing staff provided individualized guidance and emotional support, encouraged patient participation, and reminded patients to attend scheduled follow-up visit. The intervention period was 24 weeks.

LIE group: Patients in the LIE group underwent low-intensity treadmill training (EMAX58, Nanjing Han Ya Health Technology Co., Ltd.) three times per week for 24 weeks, with each session lasting 30 minutes on non-dialysis days. Peak oxygen consumption (peak VO_2) was assessed using cardiopulmonary exercise testing (CPET). Initially, exercise intensity was individualized according to each patient's baseline CPET-derived peak VO_2 (50% of individual peak), with a standardized progression proto-

col of a 10 N resistance increase every 2-3 weeks according to individual tolerance, while the duration of the exercise phase was maintained at 5-15 minutes based on the patient's exercise capacity. Exercise was immediately discontinued if patients developed any of the following symptoms, including chest tightness, excessive sweating, dizziness, pallor, muscle cramps, nausea, or abnormal breathing patterns. Exercise sessions were symptom-limited, and followed predefined termination criteria to ensure patient safety. The intervention period was 24 weeks.

Combination (DHE + LIE) group: Patients in the combination group received standard care combined with both the WeChat-based DHE intervention and the low-intensity treadmill training. To ensure intervention fidelity, the digital and exercise components were implemented by separate personnel. Potential contamination between interventions was minimized by conducting exercise sessions in the hospital gym and delivering digital education exclusively through dedicated WeChat groups. The intervention lasted for 24 weeks.

Data collection

Demographic and clinical characteristics, including age, sex, disease duration, dialysis duration, and underlying comorbidities, were collected from the electronic medical record system.

Cardiovascular function and exercise endurance were evaluated using two complementary approaches. CPET was performed at baseline and at the 24-week follow-up after intervention using an exercise cardiopulmonary assessment system. The testing protocol consisted of four sequential phases: a 3-minute resting phase, a 3-minute unloaded warm-up phase, an incremental exercise phase with gradually increasing workload by 10-15 W per minute at a constant speed of 55-60 r/min until symptom-limited termination, and a 3-minute recovery phase at 20-40 r/min until complete cessation. Anaerobic threshold (AT) and peak VO_2 were recorded as the primary cardiopulmonary parameters. In addition, functional exercise capacity was assessed using the 6-minute walk test (6MWT), which was performed at baseline and after the 24-week intervention.

Health-related quality of life was assessed using the Short Form-36 Health Survey (SF-36) at baseline and after 24-week intervention [13]. The SF-36 consists of 36 items covering eight dimensions: overall health, physiological role, social functioning, physical discomfort, mental health, vitality, and emotional functioning. Each dimension is scored from 0 to 100, with higher scores indicating better quality of life.

Self-management ability was assessed at baseline and after 24 weeks using a validated self-management ability scale [14]. The scale evaluates dimensions including health literacy, self-care responsibility, and self-care skills. Higher scores indicate better self-management ability.

Depressive symptoms were assessed using the Self-Rating Depression Scale (SDS) at baseline and after the 24-week intervention [15]. The SDS consists 10 positively worded items and 10 negatively worded items. Higher scores indicate greater severity of depressive symptoms, whereas lower scores represent better psychological status.

Nutritional status was evaluated using the Subjective Global Assessment (SGA) scale at baseline and after 24-weeks of intervention [16]. The scale evaluates six subjective nutritional markers, with each scoring 1 to 5 and totaling 6 to 30. A total score of ≤ 12 indicates severe malnutrition, 13-24 of mild-to-moderate malnutrition, and ≥ 25 of good nutritional condition.

Biochemical assays: Fasting venous blood samples were collected before the dialysis session at baseline and at the 24-week follow-up. Serum albumin (Alb) and prealbumin (PA) were measured by immunoturbidimetric assays (Roche Cobas c701, Switzerland). High-sensitivity C-reactive protein (hs-CRP) was quantified by particle-enhanced immunoturbidimetry (detection limit 0.1 mg/L). Serum myostatin was determined by enzyme-linked immunosorbent assay (ELISA; R&D Systems, USA). All assays were performed in a single batch by technicians blinded to group allocation.

The incidence of adverse events (AEs) occurring during the intervention period was recorded. The incidence of AEs was calculated as

(number of patients experiencing adverse events/total number of patients receiving intervention) $\times$ 100%. Recorded adverse events included hypoglycemia (blood glucose < 3.9 mmol/L during dialysis), bleeding (puncture-site bleeding or bleeding within the dialysis tubing), infection (redness, warmth, pain, exudation, or other inflammatory signs), and vomiting.

Patient satisfaction after the 24-week intervention was assessed using the Newcastle Satisfaction with Nursing Scales (NSNS) [17]. The total score ranges from 0 to 100 points, with scores ≥ 80 indicating high satisfaction, 60-80 indicating moderate satisfaction, and ≤ 59 indicating dissatisfaction. Overall satisfaction rate (%) = (Number of highly satisfied cases + number of moderately satisfied cases)/Total number of cases $\times$ 100%.

All follow-up assessments were conducted by researchers who had received standardized training and used uniform assessment instruments. To ensure data accuracy, double data entry and cross-validation procedures were implemented. Throughout the follow-up period, strict adherence to the study protocol was maintained to ensure data completeness and reliability.

Statistical analysis

Statistical analyses were performed using SPSS 27.0. The normality of continuous variables was assessed using the Shapiro-Wilk test. Continuous variables were expressed as mean $\pm$ standard deviation (SD). One-way ANOVA was used to compare continuous variables among the four groups at each time point, followed by least significant difference (LSD) post-hoc tests for pairwise comparisons when equal variances were assumed, or Games-Howell tests when variances were unequal.

Repeated-measures ANOVA was used to analyze time $\times$ group interactions for outcomes measured at both baseline and 24 weeks. Within-group differences between baseline and 24 weeks were evaluated using paired t-tests. Categorical variables were presented as frequencies (percentages) and compared using the chi-square test or Fisher's exact test, as appropriate. A two-sided $P < 0.05$ was consid-

Table 1. Comparison of baseline characteristics among the four groups

	Control group (n=50)	DHE group (n=50)	LIE group (n=50)	Combination group (n=50)	χ^2/F	P
Sex (n)					0.439	0.932
Male	31	32	33	34		
Female	19	18	17	16		
Age (year)	58.20±13.17	57.53±12.84	58.09±13.21	59.30±12.05	0.167	0.919
Duration of illness (years)	2.27±0.40	2.21±0.42	2.24±0.38	2.20±0.43	0.300	0.825
Duration of dialysis (years)	1.52±0.32	1.48±0.35	1.53±0.32	1.46±0.44	0.419	0.740
Underlying disease (n)					3.261	0.953
Hypertensive nephropathy	19	18	17	16		
Diabetic nephropathy	14	13	12	9		
Glomerulonephritis	13	15	16	20		
Other	4	4	5	5		

ered statistically significant. Bonferroni correction was applied for multiple pairwise comparisons when necessary.

Results

Baseline characteristics

No significant differences were observed among the four groups in sex, age, disease duration, dialysis duration, or underlying disease (all $P>0.05$), indicating comparable baseline characteristics among the groups (**Table 1**).

Exercise endurance

At 24 weeks after intervention, the combination group achieved the highest AT, significantly exceeding that in both the DHE and LIE groups (both $P<0.05$). Similarly, the 6MWT distance in the combination group was significantly greater than those in the LIE, DHE, and control groups (all $P<0.05$). Peak VO_2 showed no significant difference among-group differences at 24 weeks ($P>0.05$) (**Table 2**).

Quality of life

After 24 weeks of intervention, the combination group showed significantly higher scores than the control group across all SF-36 domains (all $P<0.05$). Moreover, the combination group scored significantly higher than both single-intervention groups in general health, physiological function, vitality, and mental health (all $P<0.05$). The LIE group showed greater improvement in physical functioning and bodily pain than the DHE alone group, whereas the DHE

group exhibited greater improvement in social functioning and emotional role than the LIE group (all $P<0.05$) (**Figure 1**).

Self-management abilities

Within-group comparisons showed that scores for all three self-management dimensions significantly increased after intervention compared with baseline levels in all four groups ($P<0.05$). Significant differences were observed among the four groups after intervention (all $P<0.05$). Pairwise comparisons revealed that the scores for all three indicators in the DHE, the LIE, and combination groups were significantly higher than those in the control group ($P<0.05$). Moreover, the combination group achieved significantly higher scores than both the DHE and LIE groups ($P<0.05$), whereas no significant differences were observed between the DHE and LIE groups (**Table 3**).

Depressive symptoms

Within-group comparison showed that depressive symptom scores significantly decreased after intervention in all four groups compared with baseline values ($P<0.05$). The difference in SDS scores among the four groups after intervention was statistically significant ($P<0.05$). Post-hoc pairwise comparisons revealed that the LIE and combination groups exhibited significantly lower SDS scores than the control group ($P<0.05$). The combination group also had significantly lower SDS scores than both the DHE and LIE groups ($P<0.05$). No significant differences were observed between the DHE

Table 2. Comparison of exercise endurance among the four groups before and after intervention

	Control group (n=50)	DHE group (n=50)	LIE group (n=50)	Combination group (n=50)	F	P
Peak VO ₂ (mL/min × kg)						
Before intervention	14.45±3.29	14.82±3.44	14.63±3.38	15.10±3.57	0.330	0.804
After intervention	15.23±2.83	15.41±3.72	15.82±3.56	15.70±2.11	0.371	0.774
AT (mL/min × kg)						
Before intervention	10.82±2.63	10.58±2.41	11.03±2.64	10.66±2.41	0.353	0.787
After intervention	12.05±2.55*	12.34±3.21*	13.12±3.23*	14.81±3.58 ^{a,b,c}	7.661	<0.001
6MWT (m)						
Before intervention	408.39±62.17	413.73±66.47	410.00±63.44	417.89±67.79	0.212	0.888
After intervention	438.43±46.73*	450.46±60.68*	465.37±58.91 ^a	492.20±61.24 ^{a,b,c}	3.194	0.025

Notes: Peak VO₂, peak oxygen consumption; AT, anaerobic threshold; 6MWT, 6-minute walk test. *P<0.05, compared with baseline levels within the group; ^aP<0.05, compared with control group after the intervention; ^bP<0.05, compared with DHE group after the intervention; ^cP<0.05, compared with LIE group after the intervention.

and control groups, as well as between the DHE and LIE groups (P>0.05) (**Table 4**).

Nutritional status

Within-group comparisons indicated that nutritional status scores significantly increased after intervention in all four groups compared with baseline levels (P<0.05). Significant differences in nutritional status scores were observed among the four groups after intervention (P<0.05). Pairwise comparisons indicated that the DHE, LIE, and combination groups had remarkably higher nutritional status scores than the control group (P<0.05); the combination group achieved significantly higher scores than both the DHE and LIE groups (P<0.05), whereas no obvious difference was observed between the DHE and LIE groups (P>0.05) (**Table 5**).

Biochemical markers

Intra-group comparisons showed that, after 24-week intervention, serum Alb and PA levels were significantly elevated, whereas hs-CRP and myostatin levels were markedly decreased in all four groups compared with baseline values (all P<0.05). Significant differences among the four groups were observed for all four biomarkers after intervention (all P<0.001). Post-hoc pairwise comparisons demonstrated that the DHE, LIE, and combination groups had significantly higher Alb and PA levels and significantly lower hs-CRP and myostatin levels compared with the control group (all P<0.05). Furthermore, the combination group achieved significantly greater improvements in all four

biomarkers than both the DHE and LIE groups (all P<0.05). No significant differences were detected between the DHE and LIE groups (P>0.05) (**Table 6**).

Adverse reactions and patient satisfaction

Following a 24-week intervention, the overall incidence rates of AEs were 22.0% (11/50) in the control group, 12.0% (6/50) in the DHE group, 10.0% (5/50) in the LIE group, and 6.0% (3/50) in the combination group (**Figure 2**). According to the chi-square test results, there was no statistically significant difference in the overall incidence of adverse reactions among the four groups ($\chi^2=6.354$, P=0.096).

Regarding patient satisfaction, the overall satisfaction rates were 82.0% (41/50) in the control group, 88.0% (44/50) in the DHE group, 90.0% (45/50) in the LIE group, and 96.0% (48/50) in the combination group. The difference in overall satisfaction rates among the four groups did not reach statistical significance ($\chi^2=6.568$, P=0.363) (**Figure 3**).

Discussion

This four-arm randomized study was conducted to evaluate the independent and combined effects of DHE and LIE in patients undergoing MHD. Our findings demonstrate that both DHE and LIE provided positive benefits compared with standard care, while their combination consistently produced greater improvements across multiple domains, including exercise tolerance, nutritional status, systemic inflammation, and quality of life. These findings provide

Digital health education and exercise in hemodialysis

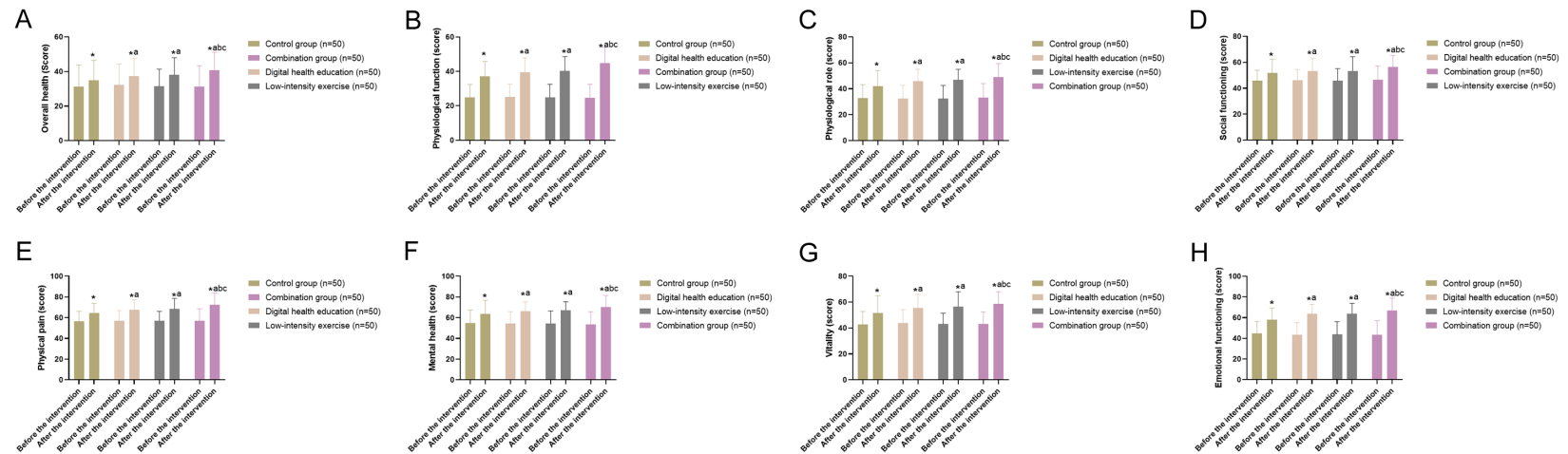


Figure 1. Comparison of quality-of-life scores (SF-36) before and after 24-week intervention. (A) General health, (B) Physiological function, (C) Physiological role, (D) Social functioning, (E) Vitality, (F) Physical pain, (G) Mental health, (H) Emotional functioning. Notes: * $P < 0.05$, compared with baseline levels within the group; ^a $P < 0.05$, compared with control group after the intervention; ^b $P < 0.05$, compared with DHE group after the intervention; ^c $P < 0.05$, compared with LIE group after the intervention.

Table 3. Comparison of self-management abilities among the four groups before and after intervention

	Control group (n=50)	DHE group (n=50)	LIE group (n=50)	Combination group (n=50)	<i>f</i>	<i>p</i>
Sense of responsibility for self-care						
Before intervention	27.92±3.15	28.10±3.24	27.67±3.46	27.40±3.55	0.412	0.744
After intervention	33.77±3.97*	36.23±3.34 ^a	37.48±3.62 ^a	40.54±3.33 ^{a,b,c}	31.028	<0.001
Self-care skills						
Before intervention	23.81±2.91	24.11±3.02	23.72±3.38	23.14±3.44	0.806	0.492
After intervention	36.58±3.65*	39.33±3.57 ^a	40.61±3.69 ^a	44.96±3.81 ^{a,b,c}	44.984	<0.001
Health literacy						
Before intervention	30.85±3.10	31.11±3.23	30.41±3.14	31.36±3.20	0.821	0.484
After intervention	37.32±3.13*	40.94±3.51 ^a	41.72±3.68 ^a	45.35±3.96 ^{a,b,c}	42.260	<0.001

Notes: **P*<0.05, compared with baseline levels within the group; ^a*P*<0.05, compared with control group after the intervention; ^b*P*<0.05, compared with DHE group after the intervention; ^c*P*<0.05, compared with LIE group after the intervention.

Table 4. Comparison of depressive symptoms among the four groups

	Control group (n=50)	DHE group (n=50)	LIE group (n=50)	Combination group (n=50)	<i>F</i>	<i>P</i>
Before intervention	35.16±8.12	36.11±8.34	35.37±7.90	36.19±7.75	0.609	0.544
After intervention	28.40±8.13*	26.88±7.27*	25.46±7.11 ^a	22.55±6.94 ^{a,b,c}	5.698	<0.001

Notes: **P*<0.05, compared with baseline levels within the group; ^a*P*<0.05, compared with control group after the intervention; ^b*P*<0.05, compared with DHE group after the intervention; ^c*P*<0.05, compared with LIE group after the intervention.

Table 5. Comparison of nutritional status among the four groups

	Control group (n=50)	DHE group (n=50)	LIE group (n=50)	Combination group (n=50)	<i>F</i>	<i>P</i>
Before intervention	14.89±2.89	15.37±2.83	15.19±2.85	15.21±2.71	0.252	0.860
After intervention	19.24±3.83*	21.38±2.48 ^a	22.38±2.81 ^a	25.76±2.36 ^{a,b,c}	43.050	<0.001

Notes: **P*<0.05, compared with baseline levels within the group; ^a*P*<0.05, compared with control group after the intervention; ^b*P*<0.05, compared with DHE group after the intervention; ^c*P*<0.05, compared with LIE group after the intervention.

Table 6. Comparison of serum biomarker levels among the four groups before and after intervention

	Control group (n=50)	DHE group (n=50)	LIE group (n=50)	Combination group (n=50)	<i>F</i>	<i>P</i>
Alb (g/L)						
Before intervention	36.22±3.16	36.37±2.96	36.80±2.52	36.52±3.23	0.345	0.793
After intervention	40.04±4.37*	42.17±3.92 ^a	42.82±4.20 ^a	44.46±3.94 ^{a,b,c}	8.748	<0.001
PA (mg/L)						
Before intervention	238.40±30.26	232.36±26.31	234.93±28.65	235.23±34.82	0.336	0.779
After intervention	266.42±45.23*	283.46±28.65 ^a	290.90±31.73 ^a	329.27±33.55 ^{a,b,c}	13.820	<0.001
hs-CRP (mg/L)						
Before intervention	11.08±2.93	11.17±2.86	10.12±3.22	10.36±2.88	1.536	0.207
After intervention	9.56±4.71*	8.16±4.68 ^a	6.61±4.31 ^a	4.77±1.54 ^{a,b,c}	20.830	<0.001
Myostatin (ng/mL)						
Before intervention	16.79±2.60	16.33±2.94	17.64±2.22	16.88±3.10	1.970	0.120
After intervention	15.24±3.49*	14.14±3.71 ^a	13.34±2.78 ^a	11.00±3.91 ^{a,b,c}	11.671	<0.001

Notes: Alb, albumin; PA, prealbumin; hs-CRP, C-reactive protein. **P*<0.05, compared with baseline levels within the group; ^a*P*<0.05, compared with control group after the intervention; ^b*P*<0.05, compared with DHE group after the intervention; ^c*P*<0.05, compared with LIE group after the intervention.

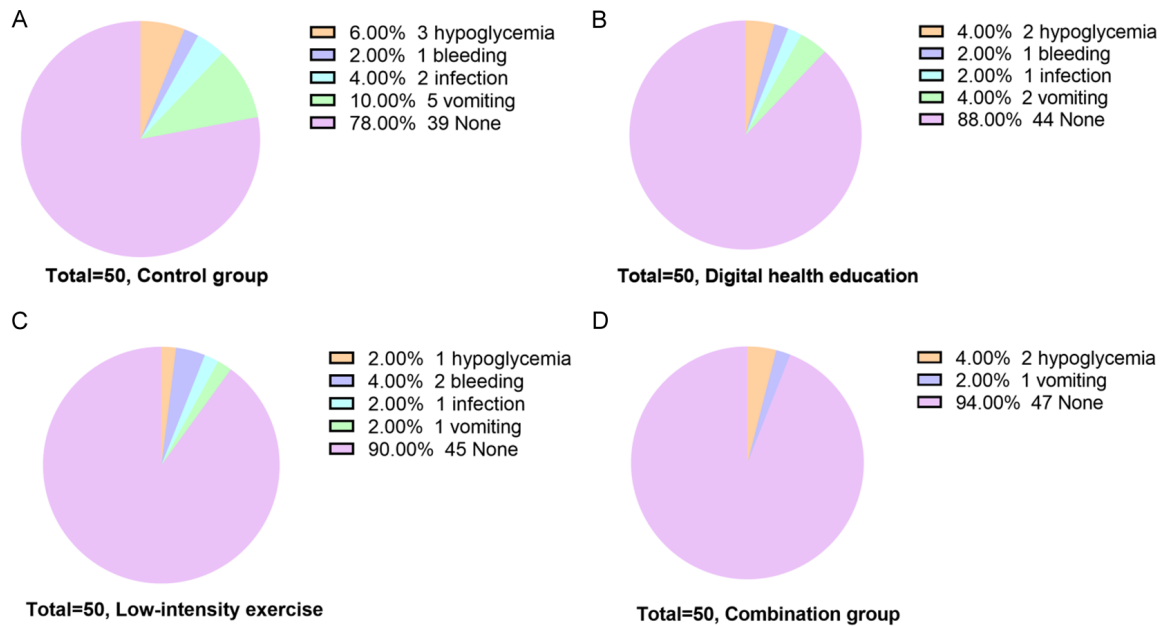


Figure 2. Distribution of adverse reactions in the four groups. A. Adverse reactions in the control group. B. Adverse reactions in the digital health education group. C. Adverse reactions in the low-intensity exercise group. D. Adverse reactions in the combination group.

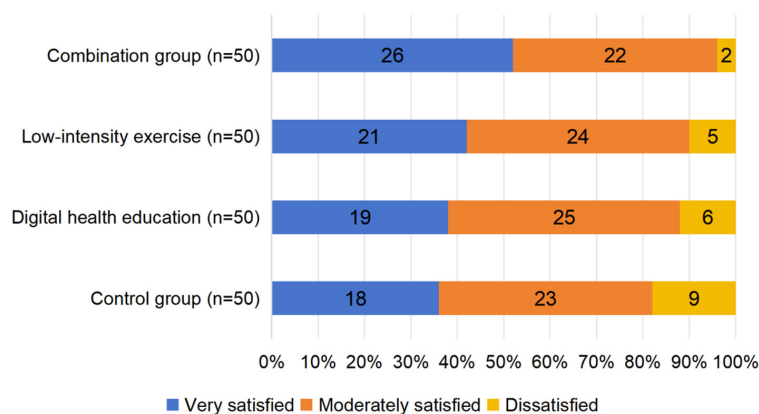


Figure 3. Distribution of satisfaction levels in the four groups.

novel insights into the component-specific effects of a composite rehabilitation model and offer evidence-based implications for optimizing nursing care in this population.

The differential improvements in cardiopulmonary function among the four groups require careful interpretation. At 24 weeks, AT and 6MWT performance were significantly improved in all intervention groups compared with the control group, with the combination group showing the greatest improvements. However, no significant changes were observed in peak

VO_2 in any group, including the LIE and combination groups. This pattern may reflect differences in the physiological responses represented by these exercise parameters. AT, a submaximal indicator reflecting aerobic capacity during moderate-intensity activities, is considered more sensitive to sustained low-to-moderate intensity aerobic training [18]. Low-intensity exercise, as applied in our protocol (50% of individual peak VO_2), can effectively enhance mitochondrial function and oxidative meta-

bolism, leading to improvements in AT and 6MWT [19]. In contrast, peak VO_2 , an indicator of maximal aerobic capacity, generally requires higher-intensity exercise or combined aerobic-resistance training to achieve significant improvement, as reported in previous meta-analyses [20, 21]. Therefore, the absence of significant peak VO_2 improvement in the LIE and combination groups may be explained by the relatively low exercise intensity and training dose used in this study [22]. Importantly, the addition of DHE to LIE did not further improve peak VO_2 , suggesting that the limita-

tion may be related primarily to the prescribed exercise intensity rather than intervention adherence. This interpretation is supported by the finding that DHE alone also improved AT and 6MWT, likely through enhanced exercise adherence and optimized daily activity patterns, rather than direct physiological stimulation [8].

The observed changes in biochemical markers further support the potential physiological benefits of the interventions. Serum albumin and prealbumin, commonly used indicators of nutritional status, significantly increased in all intervention groups, with the combination group achieving the greatest improvements. These findings suggest that both DHE and LIE contribute to improved nutritional status through complementary pathways. LIE may promote protein synthesis through exercise-related adaptations, whereas DHE improves dietary behaviors by enhancing nutritional knowledge and adherence to dietary recommendations [23]. Serum myostatin, a negative regulator of muscle growth, showed the greatest reduction in the combination group. Decreased myostatin activity is associated with improved muscle mass and function, and our findings indicate that the combined intervention most effectively suppresses this catabolic pathway. The significant reduction in hs-CRP, particularly in the combination group, suggests a potential additive anti-inflammatory effect of integrating DHE with LIE [24, 25]. Low-intensity exercise has been reported to modulate systemic inflammation by reducing pro-inflammatory cytokine production, whereas DHE may contribute indirectly through improved dietary behaviors, enhanced disease management, and reduced psychological burden [26]. The potential synergistic effects of the combined intervention may involve multiple pathways, including improved health literacy through structured education, enhanced social support through digital communication, and reinforcement of healthy behaviors through regular reminders and nurse feedback.

The differential effects of DHE and LIE on quality of life and self-management abilities warrant further consideration. Although both interventions improved SF-36 scores compared with standard care, the combination group demonstrated consistently greater improve-

ments than either single-intervention groups across multiple domains. Notably, LIE alone showed greater benefits in physical functioning and bodily pain, whereas DHE alone produced greater improvements in social functioning and role limitations due to emotional problems. This pattern may reflect the distinct contributions of the two interventions: LIE directly improves physical capacity and reduces somatic discomfort [27, 28], whereas DHE enhances social interaction, emotional support, and health-related knowledge through peer communication and structured education delivered via the WeChat platform [29]. These findings highlight the complementary effects of the two interventions. Regarding self-management ability, the DHE group demonstrated greater improvement in health literacy, whereas the LIE group demonstrated greater improvement in self-care skills. This suggests that digital education may be particularly effective in promoting knowledge acquisition, while physical training may reinforce practical self-care behaviors through repeated practice and behavioral reinforcement. The superior performance of the combination group across all self-management dimensions indicates that these mechanisms may not be mutually exclusive but rather work synergistically.

The changes in depressive symptoms assessed by the SDS showed a similar pattern. All intervention groups showed significant reductions in SDS scores, with the LIE group demonstrating greater improvement than the DHE group, and the combination group achieving the lowest SDS scores. These findings are consistent with previous evidence suggesting that regular exercise may alleviate depressive symptoms through multiple neurobiological pathways, including modulation of neurotransmitter activity involving serotonin, norepinephrine, and dopamine, as well as endorphin-related mood regulation [1]. Although DHE alone also contributed to improvements in depression, likely through enhanced social support and reduced anxiety, its effect size was smaller than that of LIE. The additional benefit observed in the combination group suggests that the psychological benefits of exercise and digital education may involve partially independent pathways that can be synergistically integrated. This finding is clinically meaningful, as depression is highly prevalent in MHD patients

and may adversely affect treatment adherence, nutritional intake, and overall prognosis [30].

Regarding nutritional status, the SGA scores indicated that LIE alone produced greater improvements than DHE alone, whereas the combined intervention resulted in the greatest improvement. This suggests that physical training may exert a more direct influence on nutritional status, likely through improved appetite, enhanced protein metabolism, and attenuation of inflammation-related catabolic processes [31]. DHE alone also significantly improved nutritional outcomes, although to a lesser extent, possibly through improved dietary awareness and optimized dietary behaviors. The synergistic effect observed with the combined intervention may be related to simultaneous improvements in both nutritional intake (facilitated by DHE) and physical function (enhanced by LIE), addressing the multifactorial mechanisms underlying malnutrition in MHD patients.

In addition, the combination group outperformed the single-intervention group in terms of increased serum Alb and PA levels and decreased hs-CRP and myostatin levels. Alb and PA are commonly used indicators of nutritional status and protein synthetic function. Patients undergoing MHD are particularly susceptible to hypoalbuminemia due to protein loss during dialysis, reduced appetite, and chronic inflammatory conditions [32]. In this study, the improvements in Alb and PA levels observed in the LIE group may be related to exercise-induced metabolic adaptations, while the DHE group may have benefited from improved dietary behaviors and protein intake through structured dietary education. The combined intervention, which integrated both approaches, may have simultaneously promoted nutritional management and metabolic adaptation.

hs-CRP, a marker of systemic low-grade inflammation, decreased significantly in both the LIE group and the combined intervention group, suggesting a potential anti-inflammatory effect of regular low-intensity exercise. A systematic review and meta-analysis has demonstrated that exercise interventions can reduce inflammatory marker levels in patients with chronic kidney disease [33]. The underlying mechanisms may involve modulation of inflammatory signaling pathways, including the NF- κ B and

STAT3 pathways, thereby reducing inflammatory cytokine-mediated muscle protein degradation. hs-CRP levels also decreased significantly in the DHE group, although to a lesser extent than in the exercise group; this may be partly attributed to improved disease management through the WeChat platform, including guidance on diet, medication adherence, and infection prevention, which may reduce potential inflammatory triggers.

Myostatin is a negative regulator of skeletal muscle growth, and its levels are negatively correlated with muscle strength and walking speed. In this study, myostatin levels in all three groups decreased significantly from baseline following intervention, with the combination group showing the greatest reduction. However, several factors should be considered when interpreting these findings. First, this study measured serum myostatin levels rather than skeletal muscle tissue expression. Second, the exercise intervention consisted of low-intensity aerobic training rather than resistance training, which is more directly associated with muscle hypertrophy. Therefore, although the reduction in serum myostatin may suggest a potential improvement in muscle-related metabolic regulation, the underlying biological mechanisms remain uncertain. Notably, Zhou et al. [34], in a sub-study of the RENEXC trial, reported that plasma myostatin levels increased after 12 months of exercise training and were positively correlated with muscle mass and physical performance. These findings indicate that circulating myostatin may reflect overall muscle mass rather than simply representing a marker of muscle catabolism. Therefore, the exact pathophysiological significance of the decrease in myostatin observed in this study should be interpreted with caution, as these changes may be influenced by multiple factors, including muscle mass, inflammatory status, and metabolic adaptation.

The incidence of adverse reactions in the combined group (6.0%) was lower than that in the control group (22.0%) and the single-intervention group, while the combination group demonstrated the highest satisfaction rate (96.0%). The relatively low incidence of adverse events may be related to several factors. First, the low-intensity exercise protocol was

designed to minimize exercise-related risks, and predefined termination criteria (e.g., chest tightness, excessive sweating, and dizziness) further enhanced safety monitoring; Second, real-time communication and feedback regarding diet, medication, and symptoms through the WeChat platform may have facilitated early identification and management of potential problems. However, the inter-group comparison of adverse reactions did not reach statistical significance ($P=0.812$). Therefore, the combined intervention cannot be considered to significantly reduce the incidence of adverse reactions, but should be interpreted as a potential trend indicating favorable safety.

Limitations

This study has several limitations. First, as a single-center randomized trial, the sample may not fully represent MHD patients in other regions or healthcare settings, which may limit the external generalizability of the findings. Due to limited resources, multicenter validation was not feasible; therefore, future studies involving larger multicenter cohorts are needed to confirm the applicability of these findings. Second, the 24-week follow-up precludes assessment of long-term clinical outcomes, including all-cause mortality, cardiovascular events, dialysis access complications, and long-term changes in muscle. Future studies with extended follow-up are needed to determine the sustained clinical benefits of the intervention. Third, the requirement for smartphone proficiency as an inclusion criterion may have introduced selection bias, as elderly patients or those with limited digital literacy may have been underrepresented. Future studies should explore simplified digital platforms or hybrid intervention models to enhance accessibility and inclusiveness. Fourth, outcome assessors were not blinded to group allocation, which may have introduced detection bias for subjective outcomes (e.g., SF-36, SDS, NSNS). Although CPET-derived measures (AT, peak VO_2) and 6MWT are relatively objective measures, the possibility of assessment bias cannot be completely excluded. Fifth, this study adopted a standardized intervention protocol without stratification by baseline nutritional status, cardiopulmonary reserve, or depression severity, hindering exploration of differential treatment effects. Future research should investigate stratified digital rehabilita-

tion strategies to facilitate personalized management. Sixth, this study was not designed or powered to perform subgroup analyses. Future studies with larger samples and pre-specified stratification factors (e.g., diabetic nephropathy status, dialysis vintage, sarcopenia) are needed to identify patient characteristics associated with differential responses to intervention. Seventh, the digital health education intervention included both Western medicine and TCM content; this study was not designed to disentangle their relative contributions. Future studies may compare Western medicine-only, TCM-only, and combined content to optimize strategies. Finally, although SOP manuals enhanced standardization, differences in interpersonal communication and emotional support across nurses could not be fully eliminated. Future research should introduce intervention fidelity monitoring to enhance replicability.

Conclusion

Both digital health education and low-intensity exercise independently provided clinical benefits in patients undergoing maintenance hemodialysis. However, their combination resulted in greater improvements across multiple functional and patient-centered outcomes, including cardiopulmonary exercise capacity, nutritional status, inflammatory markers, self-management ability, and quality of life. The potential benefits of these two interventions appear to be complementary: digital health education focuses on behavioral and psychological improvements, while exercise focuses on physiological and functional improvements. This provides theoretical support for the adoption of a comprehensive rehabilitation model.

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Disclosure of conflict of interest

None.

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Digital health education and exercise in hemodialysis

Supplementary Table 1. Structured interactive assessment form for wechat-based digital health education

Part A. Basic information			
Patient name		Patient ID/Dialysis No.	
Group (n=50)	☐ DHE group ☐ Combination group	Assessment date ____/____/____	
Responsible nurse		Assessment weekday ☐ Tuesday ☐ Thursday	
Interaction type	☐ Text message ☐ Voice message	Question received time ____:____	
	☐ Image/video ☐ Video Q&A		
Part B. Patient question record and response timeliness			
Item	Content	Category	√
Question content (brief summary)		☐ Diet/fluid & potassium restriction ☐ Medication management ☐ Dialysis care ☐ Exercise guidance ☐ Western medicine knowledge ☐ TCM health-preservation knowledge ☐ Emotional/psychological support ☐ Other: _____	
Response provided by	☐ Responsible nurse ☐ Attending physician (jointly)	Response completion time	____:____
Timeliness item	Standard	Result	√
Response time limit	≤ 4 hours from question received	____ hours ____ min	☐ Yes ☐ No
Part C. Standardized assessment items (scored by responsible nurse, 0-2 points per item)			
No.	Assessment item	Scoring criteria	Score (0-2) √
1	Understanding of Western medicine knowledge module (kidney disease, MHD precautions, dialysis care, fluid/potassium restriction)	0 = Unable to answer correctly; 1 = Partially correct, needs reinforcement; 2 = Fully correct	
2	Understanding of TCM health-preservation knowledge (Tai Chi/Ba Duan Jin guidance, relaxation & meditation, syndrome-differentiation diet)	0 = Unable to answer correctly; 1 = Partially correct, needs reinforcement; 2 = Fully correct	
3	Dietary and fluid management compliance (daily morning reminder response)	0 = Non-compliant; 1 = Occasionally non-compliant; 2 = Fully compliant	
4	Medication management compliance (daily morning reminder response)	0 = Non-compliant; 1 = Occasionally non-compliant; 2 = Fully compliant	
5	Exercise participation and record uploading (≥ 3 times/week with photos/videos)	0 = Not achieved; 1 = 1-2 times/week; 2 = ≥ 3 times/week	
6	Emotional and psychological status (peer support, confidence in disease management)	0 = Negative mood, no engagement; 1 = Partially engaged; 2 = Active engagement, stable mood	
Total score (0-12)			
Part D. Monthly online video Q&A Record (first Friday of each month, 30 minutes, recorded)			
Session date ____/____/____		Session duration ____ min (standard: 30 min)	
Participants	Attending physician: _____	Patients attended (n)	____/50
	Responsible nurse: _____		
Questions collected (n) ____		Questions answered on-site (n) ____	
Video recording archived ☐ Yes ☐ No		Session quality reviewed by Head nurse: _____	
Part E. Signatures and quality control			
Responsible nurse (1st assessor)		Signature/date	
Responsible nurse (2nd assessor)		Signature/date	
Inter-rater consistency (Kappa)	☐ ≥ 0.80 (included in analysis) ☐ < 0.80 (re-assessment required)	Head nurse review	☐ Passed ☐ Returned for correction

Note: This form was used by responsible nurses to uniformly record and assess patient interactions in the dedicated WeChat groups every Tuesday and Thursday (response time limit ≤ 4 hours). Online video Q&A sessions (first Friday of each month) were recorded separately. Items in Section C were scored independently by two responsible nurses; only records with an inter-rater consistency Kappa coefficient ≥ 0.80 were included in the analysis. Disposition rule (consistent with the exercise quality control procedure): patients with a total score ≤ 4 received telephone follow-up and additional guidance on the next day. Abbreviations: DHE, digital health education; MHD, maintenance hemodialysis; TCM, traditional Chinese medicine; Alb, albumin; PA, prealbumin.