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Effects of Early Pulmonary Rehabilitation Training on Ventilator-Induced Diaphragmatic Dysfunction in ICU Mechanically Ventilated Patients: A Randomized Controlled Trial

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Abstract: *Objective*: To investigate the preventive effects of early pulmonary rehabilitation training on ventilator-induced diaphragmatic dysfunction (VIDD) in ICU mechanically ventilated patients and its impact on clinical outcomes. *Methods*: A prospective randomized controlled trial was conducted. A total of 82 mechanically ventilated patients admitted to the intensive care unit of a tertiary hospital from January 2025 to December 2025 were enrolled and randomly assigned to either the experimental group ($n = 41$) or the control group ($n = 41$) using a random number table. The control group received routine ICU care and an early mobilization protocol, while the experimental group received systematic early pulmonary rehabilitation training in addition to the control protocol. Ultimately, 75 patients completed the study. Diaphragm excursion (DE), diaphragmatic thickening fraction (DTF), maximum inspiratory pressure (MIP), duration of mechanical ventilation, ICU length of stay, incidence of VIDD, and adverse events were compared between the two groups. *Results*: On day 5 and day 7 of the intervention, DE and DTF in the experimental group were significantly higher than those in the control group ($p < 0.05$). MIP on day 7 was significantly higher in the experimental group than in the control group ($p < 0.001$). The experimental group had significantly shorter durations of mechanical ventilation (6.2 ± 2.1 days vs. 8.7 ± 3.4 days) and ICU stays (9.5 ± 3.2 days vs. 12.8 ± 4.6 days) compared to the control group ($p < 0.001$). The incidence of VIDD was significantly lower in the experimental group (15.8%, 6/38) than in the control group (40.5%, 15/37; $p = 0.017$). No significant difference was found in the incidence of adverse events between the two groups ($p > 0.05$). *Conclusion*: Early pulmonary rehabilitation training effectively improves diaphragmatic function, reduces the incidence of VIDD, shortens the duration of mechanical ventilation and ICU length of stay in mechanically ventilated patients, and demonstrates good safety.

Keywords: Pulmonary rehabilitation; Mechanical ventilation; Ventilator-induced diaphragmatic dysfunction; Diaphragmatic ultrasound; Intensive care

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1. Introduction

Mechanical ventilation (MV) is a core life-support technology in intensive care units (ICUs), with approximately 30–88% of critically ill patients requiring MV. However, while MV saves lives, it places the diaphragm in a partial or complete unloading state, leading to decreased diaphragmatic tension, muscle fiber atrophy, and contractile dysfunction, known as ventilator-induced diaphragmatic dysfunction (VIDD) [1]. Studies indicate that the incidence of VIDD ranges from 60% to 80%, and 33% of patients with VIDD fail to recover diaphragmatic function after rehabilitation fully [2]. Evidence has confirmed that diaphragmatic atrophy and functional decline can occur within 24 hours after the initiation of MV, with atrophy progressing faster than in other skeletal muscles [3].

The pathophysiology of VIDD is complex, involving multiple molecular pathways such as mitochondrial oxidative stress, excessive activation of the ubiquitin-proteasome pathway, calpain and caspase-3-mediated proteolysis, and inhibition of protein synthesis [1,3]. VIDD not only severely affects the recovery of respiratory function but also leads to weaning difficulties, prolonged MV, extended ICU stays, increased medical costs, and even higher mortality [4]. Therefore, finding effective intervention strategies to prevent and improve VIDD has become a research hotspot in the field of critical care rehabilitation.

In recent years, pulmonary rehabilitation (PR), as a comprehensive non-pharmacological intervention, has received widespread attention for its application in ICU mechanically ventilated patients [5]. Studies have shown that early rehabilitation, including physical therapy, breathing training, and exercise training, can effectively prevent and improve respiratory muscle atrophy, enhance muscle strength, reduce in-hospital mortality, and improve overall prognosis [6–8]. However, high-quality randomized controlled trials focusing on the preventive effects of early pulmonary rehabilitation centered on respiratory muscle training for VIDD remain limited, particularly in the ICU setting in China. Therefore, this prospective randomized controlled trial aims to investigate the protective effects of early pulmonary rehabilitation training on diaphragmatic function and its impact on clinical outcomes in ICU mechanically ventilated patients, providing evidence-based support for critical care nursing practice.

2. Methods

2.1. Participants

This prospective randomized controlled trial was conducted in the ICU of a tertiary hospital from January 2025 to December 2025.

2.1.1. Inclusion criteria

(1) Age ≥ 18 years;
(2) Undergoing invasive MV via orotracheal intubation or tracheostomy;
(3) Expected duration of MV ≥ 72 hours;
(4) Relatively stable hemodynamics upon ICU admission (mean arterial pressure ≥ 65 mmHg);
(5) Informed consent provided by the patient or a family member.

2.1.2. Exclusion criteria

(1) History of neuromuscular disease or diaphragmatic paralysis before ICU admission;
(2) Previous diaphragmatic surgery;

(3) Conditions unsuitable for respiratory rehabilitation (e.g., cervical spine fracture, intracranial hypertension);
(4) Severe hemodynamic instability requiring high-dose vasoactive agents;
(5) Pregnancy;
(6) Terminal illness with expected survival < 6 months.

2.1.3. Elimination criteria

(1) MV duration < 72 hours due to extubation or death;
(2) Transfer out of the ICU during the study period;
(3) Withdrawal of informed consent.

2.1.4. Sample size calculation

Using PASS 15.0, based on pre-trial results (VIDD incidence of approximately 18% in the experimental group and 42% in the control group), with $\alpha = 0.05$ (two-tailed), power $1-\beta = 0.80$, a 1:1 allocation, and accounting for a 15% dropout rate, 82 patients were required. A random number table generated by SPSS 26.0 was used by a statistician not involved in the intervention to randomly assign 82 patients to the experimental group (n = 41) and control group (n = 41). Allocation concealment was achieved using sealed envelopes. The study was approved by the hospital ethics committee (approval number: XM2025115).

2.2. Interventions

2.2.1. Control group

The control group received routine ICU care and an early mobilization protocol, including:
(1) Basic care (vital sign monitoring, airway management, oral care);
(2) Passive/active range of motion exercises (twice daily, 15–20 min each) based on consciousness and muscle strength;
(3) Head-of-bed elevation to 30–45°;
(4) Suctioning as needed;
(5) Minimal sedation strategy.

2.2.2. Experimental group

In addition to the control protocol, the experimental group received a 7-day systematic early pulmonary rehabilitation training program delivered by a trained critical care rehabilitation team (including one ICU head nurse, two ICU specialist nurses, and one respiratory therapist). All team members completed a 2-week standardized training program and passed assessments covering bedside diaphragmatic ultrasound, respiratory muscle training techniques, airway clearance techniques, early mobilization protocols, and safety monitoring.
(1) Bedside diaphragmatic ultrasound and individualized plan

Within 24 hours of enrollment, a nurse trained in diaphragmatic ultrasound assessed baseline diaphragmatic function using a bedside ultrasound system (convex probe 2–5 MHz; linear probe 7–12 MHz), measuring DE and DTF. Based on the results, along with the patient's consciousness level (RASS score), Medical Research Council score (MRC-Score), and hemodynamic status, the rehabilitation team developed an individualized pulmonary rehabilitation plan specifying training methods, intensity, frequency, and progression criteria.

(2) Progressive respiratory muscle training

Passive stimulation phase (for RASS -3 to -1 or unable to cooperate): Patients in semi-recumbent position (head-of-bed 30–45°) received passive respiratory muscle stimulation by adjusting ventilator trigger sensitivity (initial setting -3 cmH_2O, decreased by 0.5–1 cmH_2O every 24 hours to a target of -1 cmH_2O, twice daily, 15 min each) [9,10].

(3) Active training phase (for RASS -1 to +1 able to follow commands)

Included diaphragmatic breathing, deep breathing exercises, and threshold inspiratory muscle training (initial load at 30% of MIP, 10–15 breaths per session, twice daily, with load increased by 5–10% weekly up to 50% of MIP, Borg dyspnea score ≤5) [11–13]. Each session lasted 15–20 minutes with at least 4 hours between sessions.

(4) Effective coughing and airway clearance training

For conscious patients (RASS -1 to +1) able to follow commands: effective coughing training (deep inspiration – 2-second breath hold – forceful cough) and active cycle of breathing technique (ACBT) [14,15]. Manual chest compression was applied if needed.

(5) Early progressive positioning management

Daily positioning level determined by the ICU mobility scale (IMS): IMS 0–1: passive repositioning and range of motion; IMS 2–3: additional semi-recumbent active maintenance; IMS 4–5: transition to sitting at the bedside; IMS 6–7: standing or sitting in a chair [16].

(6) Dynamic diaphragmatic ultrasound monitoring and adjustment

DE and DTF were assessed at days 1, 3, 5, and 7 by the same trained nurse. Training intensity was adjusted based on diaphragmatic function trends (increase load if DTF improved by ≥ 5%; maintain if DTF decreased by ≥ 10% or no improvement; initiate enhanced stimulation if DTF < 20% for > 72 hours).

(7) Safety stopping criteria

Training was immediately stopped if any of the following occurred: heart rate > 140/min or < 40/min; new arrhythmias; systolic blood pressure >180 mmHg or <85 mmHg, or fluctuation > 20% from baseline; SpO_2 < 88% or > 5% drop from baseline; respiratory rate > 35/min; or overt patient intolerance.

2.3. Outcome measures

2.3.1. Primary outcome

VIDD incidence, defined as DTF < 20% combined with DE < 10 mm (during quiet breathing), was assessed on day 7 [14].

2.3.2. Secondary outcomes

(1) Diaphragmatic ultrasound parameters (DE and DTF) measured on days 1, 3, 5, and 7 [9].
(2) Maximum inspiratory pressure (MIP) measured on days 1 and 7 [4].
(3) Clinical outcomes: duration of mechanical ventilation (from intubation to successful extubation with spontaneous breathing ≥ 48 hours) and ICU length of stay.
(4) Adverse events

unplanned extubation, catheter displacement, falls, severe arrhythmias, and marked blood pressure fluctuations.

2.4. Statistical analysis

SPSS 26.0 was used. The per-protocol (PP) set was used for primary efficacy analysis. Normally distributed continuous data were expressed as mean ± standard deviation ($\bar{x} \pm s$) and compared using an independent samples *t*-test or repeated measures ANOVA. Non-normally distributed data were expressed as median (IQR) and compared using the Mann-Whitney U test. Categorical data were expressed as frequencies and percentages and compared using the χ^2 test or Fisher's exact test. $p < 0.05$ was considered statistically significant.

3. Results

3.1. Baseline characteristics

Of the 82 enrolled patients, 75 completed the study (38 in the experimental group, 37 in the control group). No significant differences were found between the two groups in age, sex, BMI, APACHE II score, primary diagnosis, or PaO_2/FiO_2 ratio at ICU admission ($p > 0.05$), indicating comparability.

3.2. Diaphragmatic ultrasound indicators

On days 5 and 7, DE and DTF in the experimental group were significantly higher than those in the control group ($p < 0.05$). Repeated measures ANOVA showed significant time, group, and interaction effects for both DE and DTF ($p < 0.001$) (**Table 1**).

Table 1. Comparison of DE and DTF between the two groups ($\bar{x} \pm s$)

Parameter	Group	Day 1	Day 3	Day 5	Day 7	F-time	F-group	F-interaction
DE (mm)	Experimental	13.8 ± 2.8	14.2 ± 3.1	15.9 ± 3.4	17.1 ± 3.2	42.158	8.952	12.346
	Control	14.1 ± 3.0	13.5 ± 3.2	13.2 ± 3.5	13.4 ± 3.6			
DTF (%)	Experimental	28.5 ± 6.2	27.8 ± 5.9	31.2 ± 7.1	34.6 ± 7.8	36.724	10.158	15.637
	Control	29.1 ± 6.5	26.4 ± 6.3	24.8 ± 6.8	23.5 ± 7.2			

3.3. Maximum inspiratory pressure (MIP)

On day 7, MIP in the experimental group was significantly higher than that in the control group and significantly improved from day 1 ($p < 0.001$), while no significant change was observed in the control group ($p > 0.05$) (**Table 2**).

Table 2. Comparison of MIP between the two groups (cmH_2O, $\bar{x} \pm s$)

Group	**Day 1**	**Day 7**	***t***	*p*
Experimental	38.6 ± 8.4	52.4 ± 9.7	-8.432	< 0.001
Control	39.2 ± 9.1	36.5 ± 8.8	1.856	0.068
t	-0.298	7.456		
p	0.766	< 0.001		

3.4. Clinical outcomes and VIDD incidence

The experimental group had significantly shorter duration of MV (6.2 ± 2.1 vs. 8.7 ± 3.4 days, $p < 0.001$) and ICU length of stay (9.5 ± 3.2 vs. 12.8 ± 4.6 days, $p < 0.001$). VIDD incidence was significantly lower in the experimental group (15.8% vs. 40.5%, $p = 0.017$) (**Table 3**).

Table 3. Comparison of clinical outcomes between the two groups

Outcome	Experimental (n = 38)	Control (n = 37)	t/χ^2	p
MV duration (days, $\bar{x} \pm s$)	6.2 ± 2.1	8.7 ± 3.4	-3.978 *	< 0.001
ICU LOS (days, $\bar{x} \pm s$)	9.5 ± 3.2	12.8 ± 4.6	-3.756 *	< 0.001
VIDD [n (%)]	6 (15.8)	15 (40.5)	5.70 △	0.017

3.5. Adverse events

In the experimental group, transient blood pressure fluctuations (3 cases, 7.9%) and tachycardia (2 cases, 5.3%) occurred, all resolving after pausing or reducing training intensity. No severe adverse events (unplanned extubation, catheter displacement, falls) occurred. No significant difference in total adverse events was found between the two groups ($p = 0.673$).

4. Discussion

This study demonstrates that early pulmonary rehabilitation training effectively protects diaphragmatic function in ICU mechanically ventilated patients, as evidenced by significantly higher DE and DTF in the experimental group compared to the control group ($p < 0.05$). These findings are consistent with previous studies showing that early pulmonary rehabilitation combined with bundled nursing care improves diaphragmatic excursion [6] and that inspiratory muscle training significantly enhances diaphragmatic excursion in mechanically ventilated patients [2,4]. Notably, diaphragmatic function in the control group progressively declined on days 5 and 7, confirming the pathophysiological effect of MV-induced diaphragmatic unloading and atrophy [1,3]. In contrast, the experimental group showed no decline but rather an improvement in diaphragmatic function, suggesting that early pulmonary rehabilitation effectively counteracts the adverse effects of MV on the diaphragm [17].

The VIDD incidence in the experimental group (15.8%) was significantly lower than that in the control group (40.5%), and both MV duration and ICU length of stay were significantly shortened. Given that reported VIDD incidence can reach 60–80%, and VIDD-related weaning difficulties increase complications, costs, and mortality [1,2,4], the comprehensive and phased nature of our intervention, integrating respiratory muscle training, airway clearance techniques, and early progressive positioning with ultrasound-based dynamic adjustment, likely contributed to its success. This reflects a closed-loop management concept of "assessment–intervention–reassessment" [18].

Safety is a primary concern when implementing early rehabilitation in ICU patients with critical illness, multiple catheters, and hemodynamic instability [19,20]. Consistent with prior studies, the experimental group in our study experienced only minor, transient adverse events (blood pressure fluctuations, tachycardia) that resolved quickly, with no increase in serious adverse events compared to the control group [4,5]. These results confirm that early pulmonary rehabilitation training can be safely implemented in ICU mechanically ventilated patients under close monitoring and standardized management.

5. Conclusion

Early pulmonary rehabilitation training effectively improves diaphragmatic function, reduces the incidence of VIDD, shortens the duration of mechanical ventilation and ICU length of stay in ICU mechanically ventilated patients, and demonstrates good safety. This study recommend that individualized early pulmonary rehabilitation training based on bedside ultrasound assessment be routinely implemented for mechanically ventilated patients in ICU clinical nursing practice to protect diaphragmatic function and improve patient outcomes.

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Disclosure statement

The authors declare no conflict of interest.

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