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Recovery Trajectory after Hepato-Pancreato-Biliary Surgery: Piecewise Mixed Model Analysis

Jun Won Lee[1], Chang Hyun Lee[1], Tae Sung Park[2], Myung Jun Shin[3]

[1]Department of Rehabilitation Medicine, Biomedical Research Institute, Pusan National University Hospital

[2]Department of Convergence Medical Institute of Technology, Biomedical Research Institute, Pusan National University Hospital

[3]Department of Rehabilitation Medicine, Biomedical Research Institute, Pusan National University Hospital, Pusan National University School of Medicine

Introduction

Postoperative pulmonary complications contribute substantially to delayed recovery after hepato-pancreato-biliary (HPB) surgery. Although perioperative pulmonary rehabilitation is commonly applied, long-term recovery patterns of respiratory and physical function remain unclear. This study aimed to quantitatively characterize longitudinal recovery trajectories after HPB surgery and to identify clinically relevant time windows for postoperative rehabilitation.

Methods

A retrospective longitudinal analysis was conducted on patients referred to the Department of Rehabilitation Medicine between March 2016 and December 2025. Among 2,773 patients who underwent pulmonary function, respiratory muscle strength, and physical capacity testing, 118 had undergone HPB surgery. The final analysis included 20 patients who completed at least two serial postoperative assessments. Longitudinal changes were analyzed using a piecewise linear mixed-effects model with patient-specific random intercepts across three postoperative phases: Phase 1 (0–90 days), Phase 2 (91–180 days), and Phase 3 (>180 days), adjusted for age and sex.

Results

Pulmonary function demonstrated a significant and rapid recovery during Phase 1 (0–90 days, $p<0.001$), followed by attenuated recovery in Phase 2 and a plateau in Phase 3 ($p>0.05$). In contrast, expiratory airflow indices showed substantial inter-individual variability without a consistent phase-dependent recovery pattern. Respiratory muscle strength and physical capacity exhibited exploratory improvement mainly in the early postoperative period; however, variability and missing data limited definitive phase-specific inference. Overall, minimal additional functional recovery was observed beyond 180 postoperative days at the group level.

Table 1. Phase-specific recovery slopes from piecewise linear mixed-effects models

Outcome	Phase	Estimate (B)	Standard Error (SE)	*p*-value
FVC % Predicted	Phase 1 (0-90 days)	0.267	0.076	**<0.001***
	Phase 2 (91-180 days)	0.020	0.042	0.629
	Phase 3 (>180 days)	0.004	0.004	0.323
FEV1 % Predicted	Phase 1 (0-90 days)	0.095	0.073	0.190
	Phase 2 (91-180 days)	0.070	0.041	0.086
	Phase 3 (>180 days)	0.001	0.004	0.841
MIP (cmH_2O)	Phase 1 (0-90 days)	0.262	0.126	**0.039***
	Phase 2 (91-180 days)	0.024	0.080	0.766
	Phase 3 (>180 days)	-0.002	0.013	0.883
MEP (cmH_2O)	Phase 1 (0-90 days)	-0.027	0.164	0.868
	Phase 2 (91-180 days)	0.145	0.105	0.165
	Phase 3 (>180 days)	0.010	0.017	0.552
6MWD % Predicted	Phase 1 (0-90 days)	0.309	0.103	**0.003***
	Phase 2 (91-180 days)	0.053	0.049	0.282
	Phase 3 (>180 days)	0.001	0.005	0.898

Values are estimated coefficients (B) derived from piecewise linear mixed-effects models with patient-specific random intercepts, adjusted for age and sex. Estimates represent the average change per 30 postoperative days (approximately one month). Phase 1: 0-90 days; Phase 2: 91-180 days; Phase 3: >180 days. *$p<0.05$ was considered statistically significant
FVC; forced vital capacity, FEV1; forced expiratory volume in 1 second, MIP; maximal inspiratory pressure, MEP; maximal expiratory pressure, 6MWD; 6-minute walk distance

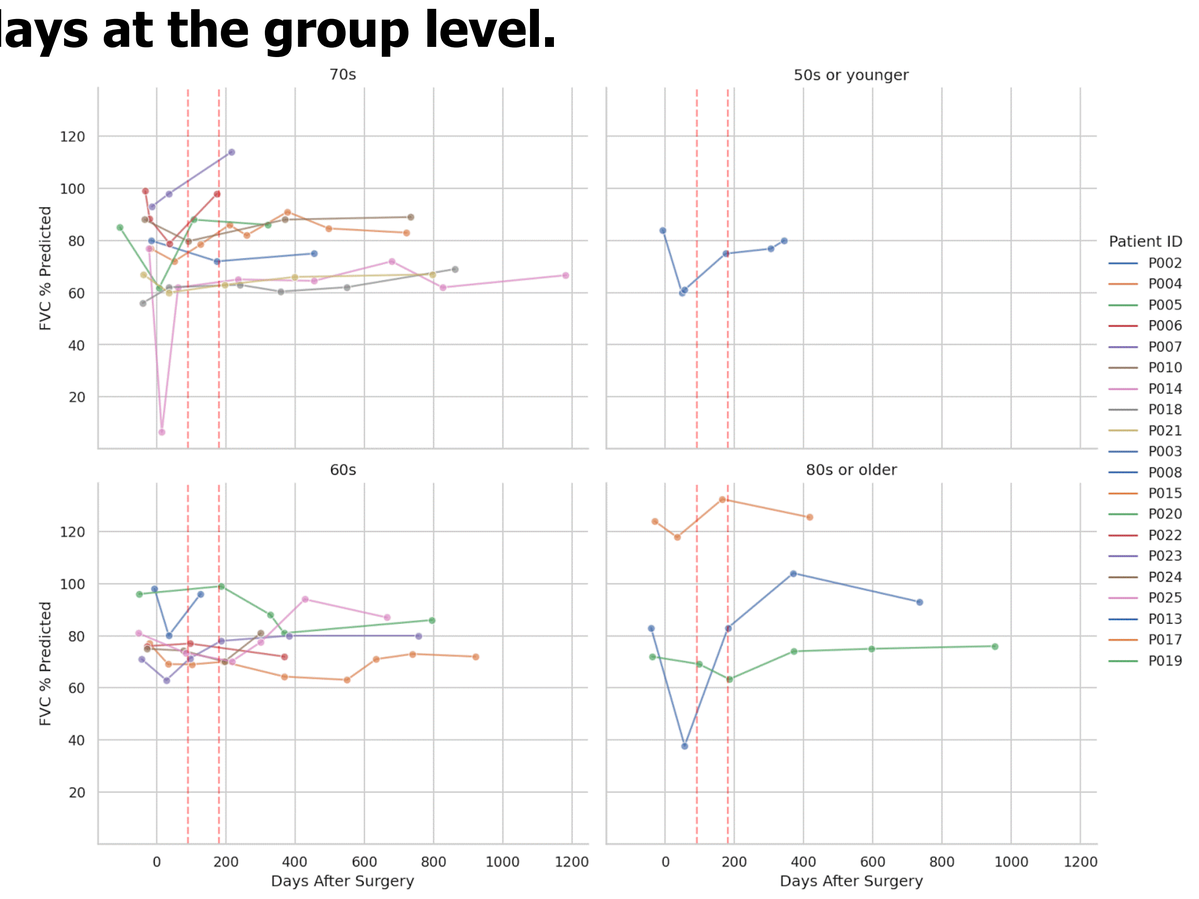

Fig 1. Longitudinal trajectories of forced vital capacity recovery after HPB surgery stratified age groups

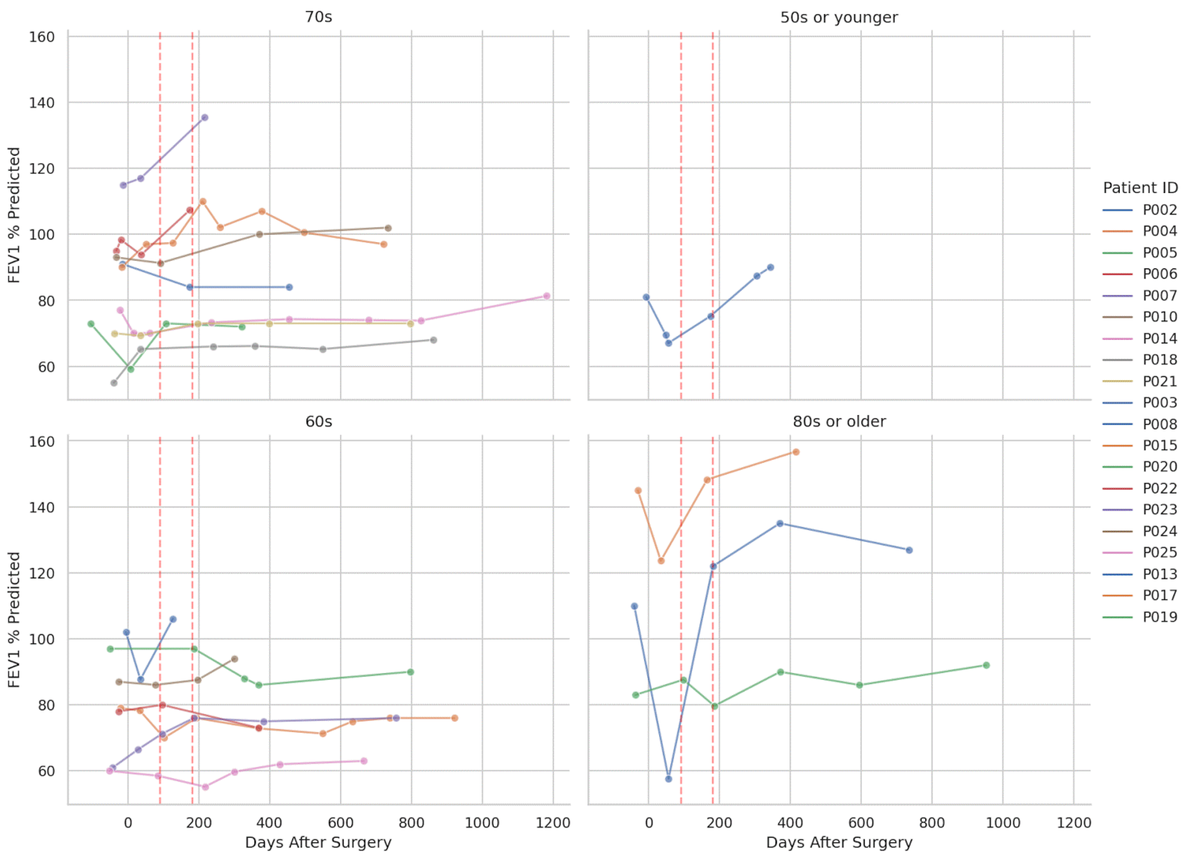

Fig 2. Age-stratified postoperative recovery patterns of forced expiratory volume in 1 second

Conclusion

Recovery of respiratory function after HPB surgery is largely concentrated within the first three postoperative months, indicating a critical early recovery window. These findings emphasize the clinical importance of timely and focused pulmonary rehabilitation during the early postoperative period to maximize functional recovery.