

Predictive Value of Cardiopulmonary Exercise Testing Parameters for Pulmonary Arterial Hypertension in Peritoneal Dialysis Patients—A Retrospective Study

Yunxiu Xie¹, Xiaonan Qiu¹, Ying Zhang^{1,*}, Ying Liu¹, Zhongcheng Yin¹

¹Department of Nephrology, Xuzhou Medical University Affiliated Hospital, Xuzhou, Jiangsu, China

*Correspondence: yingzhangxz@126.com (Ying Zhang)

Abstract

Aims/Background Pulmonary arterial hypertension (PAH) is a significant contributor to increased overall and cardiovascular mortality in peritoneal dialysis (PD) patients. Cardiopulmonary exercise testing (CPET) is an accurate method for measuring cardiorespiratory fitness (CRF) during both submaximal and peak exercise. Previous studies have demonstrated a strong correlation among CRF and increased cardiovascular and overall mortality rates. However, no literature currently reports the predictive value of CPET parameters for PAH occurrence in PD patients. This study primarily aims to analyze the risk factors for PAH in PD patients, assess the predictive value of CPET parameters, and provide a reference for the clinical prevention and management of PAH.

Methods The clinical data of 121 PD patients who underwent CPET were retrospectively collected at Xuzhou Medical University Affiliated Hospital. Based on the event of PAH, patients were divided into two groups: a PAH group (n = 39) and a non-PAH group (n = 82). Clinical data, laboratory results, ultrasound findings, and CPET parameters were compared between the groups. Multifactorial logistic regression analysis was performed to identify the risk factors for PAH. The predictive value of CPET parameters was evaluated by calculating the area under the receiver operating characteristic (ROC) curve (AUC) using ROC curve analysis.

Results White blood cell count (WBC) was an independent risk factor for PAH in PD patients ($p < 0.05$). VO_2 peak (peak oxygen uptake), VO_2 AT (anaerobic threshold oxygen uptake), METspeak (peak metabolic equivalents), WRpeak (peak power load) were identified as protective factors for PAH in PD patients ($p < 0.05$). ROC curve analysis showed that the AUC values for predicting PAH in PD patients using VO_2 peak, VO_2 AT, METspeak, and WRpeak were 0.675, 0.651, 0.719, and 0.689, respectively, with METspeak demonstrating the highest AUC for prediction.

Conclusion The occurrence of PAH in PD patients is associated with WBC, VO_2 peak, VO_2 AT, METspeak, and WRpeak. Additionally, CPET parameters exhibit predictive value for PAH, with METspeak showing the highest AUC for prediction.

Key words: cardiopulmonary exercise testing parameters; peritoneal dialysis; pulmonary arterial hypertension; retrospective study

Submitted: 29 July 2024 Revised: 20 August 2024 Accepted: 9 September 2024

How to cite this article:

Xie Y, Qiu X, Zhang Y, Liu Y, Yin Z. Predictive Value of Cardiopulmonary Exercise Testing Parameters for Pulmonary Arterial Hypertension in Peritoneal Dialysis Patients—A Retrospective Study. *Br J Hosp Med.* 2024. <https://doi.org/10.12968/hmed.2024.0469>

Introduction

Peritoneal dialysis (PD) is a renal dialysis treatment for end-stage renal disease (ESRD). It offers advantages such as ease of operation and low cost, making it a key treatment option for ESRD patients (Chuasuwana et al, 2020; Karkar and Wilkie,

2023). Recent studies have identified cardiovascular diseases as a major risk factor for mortality in ESRD patients, with pulmonary arterial hypertension (PAH) being a common cardiovascular complication (Annaiah et al, 2021; Orihuela et al, 2020). A meta-analysis revealed that the incidence of PAH in PD patients ranges from 16% to 42%, with variations primarily due to differences in study populations and PAH diagnostic criteria (Li et al, 2019). PAH, characterized by elevated pulmonary artery pressure, is a frequent cardiovascular complication in PD patients and a significant contributor to both all-cause and cardiovascular mortality. Therefore, early prediction of PAH is crucial.

Currently, right heart catheterization is the gold standard for diagnosing PAH, though it is invasive and has low patient acceptance (Rroji et al, 2021). Cardiorespiratory fitness (CRF), typically assessed via maximal oxygen consumption (VO_2 max), is considered a key predictor of cardiovascular and all-cause mortality, as supported by numerous studies (Kurl et al, 2022; Schoenberg et al, 2020). Cardiopulmonary exercise testing (CPET) is a non-invasive diagnostic tool that evaluates changes in cardiorespiratory function under exercise stress, providing insight into overall health and exercise capacity (Dewar et al, 2023; Kirkman and Chavez, 2024). CPET accurately quantifies CRF during both submaximal and peak exercise. Among the parameters measured during CPET, metabolic equivalent (MET) is considered an objective indicator of energy metabolism intensity (Wang et al, 2024b). Previous study has shown a strong association between a decrease of 2–3 MET in CRF and a significant increase in cardiovascular and all-cause mortality (Han et al, 2022). However, there is currently no literature reporting on the predictive value of CPET parameters for PAH occurrence in PD patients. This study aims to analyze the risk factors for PAH development in PD patients, evaluate the predictive value of CPET parameters, and provide a reference for the clinical prevention and treatment of PAH.

Methods

Research Objects

This study is a retrospective analysis. Clinical data were collected from PD patients who underwent CPET and were admitted to Xuzhou Medical University Affiliated Hospital between October 2022 and June 2023. The inclusion criteria were as follows: (1) clinical diagnosis of chronic kidney disease stage 5 and undergoing PD; (2) age >18 years; (3) receiving PD treatment for more than one month; (4) availability of complete laboratory and echocardiography data; and (5) complete CPET data. The exclusion criteria were: (1) presence of active infection, use of hormones, immunosuppressive agents, or PAH treatments; (2) congenital heart disease, static hypertension, or unstable blood pressure control; (3) fractures or joint damage; (4) patients undergoing combined hemodialysis; and (5) incomplete data.

Patients were divided into the PAH and non-PAH groups based on the presence of PAH. PAH was defined as a pulmonary artery pressure ≥ 35 mmHg, calculated using the modified Bernoulli equation: pulmonary artery pressure = $4 \times (\text{tricus-$

pid regurgitation maximum velocity)² + right atrial pressure (5/10/15 mmHg), as determined by echocardiography (Bech-Hanssen et al, 2023; Maron, 2023).

The clinical data of 135 PD patients were initially collected. Five patients were excluded due to incomplete data. Of the remaining 130 patients, two were excluded for severe heart disease, three for lung disease, and four for joint damage, leaving a total of 121 patients. Based on echocardiography results, patients were divided into the PAH group (n = 39) and the non-PAH group (n = 82). This study adheres to the *Declaration of Helsinki*, and ethical approval was obtained from the medical ethics committee of the Xuzhou Medical University Affiliated Hospital (Ethical batch number: XYFY2021-KL199-01).

Data Collection

Clinical data were collected from patients' electronic medical records, including age, gender, primary renal disease, dialysis duration, body mass index (BMI), smoking history, history of hypertension, history of diabetes, and admission systolic and diastolic blood pressure. Laboratory parameters such as white blood cell count (WBC), hemoglobin, albumin (ALB), blood urea nitrogen, creatinine, uric acid, estimated glomerular filtration rate (eGFR), C-reactive protein (CRP), total cholesterol, calcium, phosphorus, iron, and parathyroid hormone (PTH) were also recorded. Additionally, echocardiographic results, including left ventricular ejection fraction, interventricular septum thickness, and left ventricular end-diastolic diameter, were documented.

CPET Method

CPET includes electrocardiogram (ECG) stress testing and exercise gas exchange analysis, following the exercise testing and training standards published by the American Heart Association (Guazzi et al, 2018). The equipment consists of an exercise treadmill or bike, along with ECG (Model: CV200+, Beijing Gushanfeng Biomedical Technology Co., Ltd., Beijing, China) monitoring devices, blood pressure monitoring devices, and a gas analysis system (MasterScreen, Jaeger, Hamburg, Germany) for measuring respiratory gas exchange. Patients are required to wear ECG electrodes, typically placed on the chest, and a mask or nose clip for gas analysis to record oxygen uptake and carbon dioxide output. The test duration generally lasts between 8 and 12 minutes, and testing is scheduled between 9:00–11:00 AM or 2:00–4:00 PM. Patients are advised to wear loose clothing and athletic shoes, fast for 2 hours prior to the test, and avoid strenuous activity for 24 hours before the procedure.

The ECG stress test begins with the subject resting for 3 minutes on a cycle ergometer, followed by 3 minutes of unloaded pedaling. The load is then continuously increased by 15 W/min, maintaining a rhythm above 60 rpm until the patient reaches peak exercise or the test endpoint. ECG monitoring is performed continuously during rest, exercise, and recovery, with blood pressure measured every 2 minutes. Exercise is terminated if the heart rate reaches 85% of the predicted maximum, systolic blood pressure exceeds 220 mmHg, or if severe arrhythmias such as ST segment depression ≥ 0.2 mV or elevation ≥ 0.2 mV occur. Additionally, the

test is halted if the patient experiences symptoms like chest pain, tightness, shortness of breath, palpitations, or fatigue.

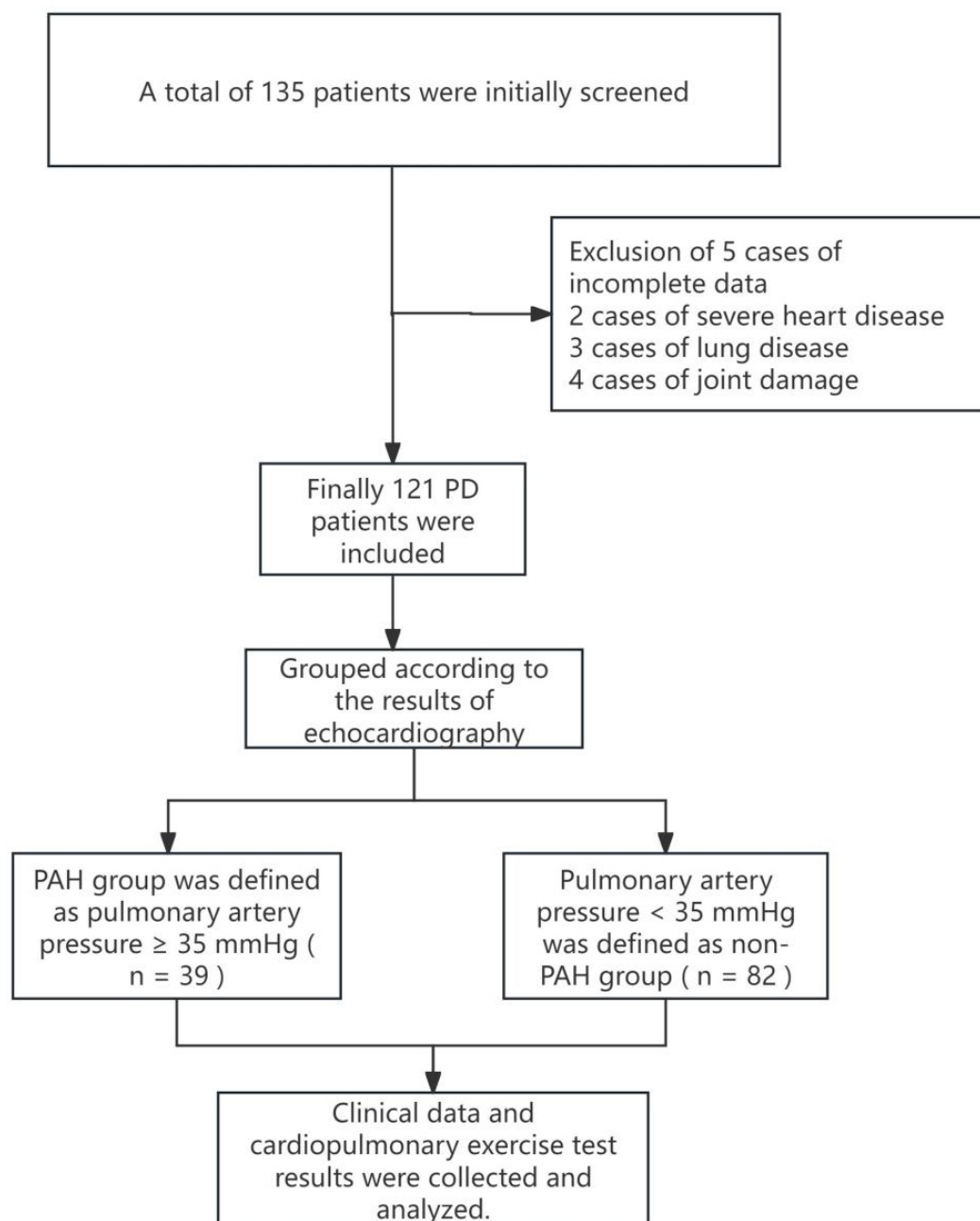


Fig. 1. Case screening flow chart. PD, peritoneal dialysis; PAH, pulmonary arterial hypertension.

During the exercise gas exchange analysis, each exhaled breath of the patient is continuously monitored using the gas exchange system, starting from the beginning of the test. The measured respiratory parameters include oxygen consumption (VO_2), carbon dioxide production (VCO_2), minute ventilation (VE), peak metabolic equivalents (MET_{peak}), and the anaerobic threshold, determined by the V-slope method. ECG monitoring continues throughout the entire CPET to ensure comprehensive data collection on both cardiopulmonary and metabolic responses.

Table 1. Baseline characteristics of study participants.

Variable	PAH group (n = 39)	Non-PAH group (n = 82)	χ^2/t value	<i>p</i> value
Gender (cases)			0.354	0.552
Male	25	57		
Female	14	25		
Age (years, $\bar{x} \pm s$)	61.25 \pm 6.94	58.48 \pm 7.88	1.876	0.063
Primary renal disease (cases)			1.077	0.584
Diabetic nephropathy	24	50		
Chronic glomerulonephritis	6	18		
Others	9	14		
Dialysis time (months, $\bar{x} \pm s$)	23.48 \pm 4.57	22.19 \pm 5.12	1.339	0.183
BMI (kg/m ² , $\bar{x} \pm s$)	22.97 \pm 1.27	23.45 \pm 1.38	1.834	0.069
Smoking history (cases)	11	20	0.202	0.653
History of hypertension (cases)	19	36	0.247	0.619
History of diabetes (cases)	25	53	0.003	0.955
Admission systolic blood pressure (mmHg, $\bar{x} \pm s$)	153.52 \pm 10.18	149.71 \pm 12.35	1.674	0.097
Admission diastolic blood pressure (mmHg, $\bar{x} \pm s$)	91.48 \pm 6.74	89.25 \pm 8.14	1.485	0.140

PAH, pulmonary arterial hypertension; BMI, body mass index.

Statistical Methods

The data were analyzed using IBM SPSS 27.0 (Armonk, NY, USA). The Kolmogorov-Smirnov (K-S) test was used to assess the normality of the data. Normally distributed metric data are presented as mean \pm standard deviation, and between-group comparisons were conducted using independent sample *t*-tests. Count data are presented as frequencies or percentages, with comparisons made using the chi-square test. Variables showing statistically significant differences in the one-way analysis were further analyzed using multiple-factor logistic regression. The receiver operating characteristic (ROC) curve was used to calculate the area under the curve to evaluate the predictive value of CPET parameters. The significance level was set at $\alpha = 0.05$.

Results

Data Selection

Data from 135 PD patients were collected. Five cases with incomplete data were excluded. Among the remaining 130 cases, 2 were excluded due to severe heart disease, 3 due to lung diseases, and 4 due to joint damage, resulting in a final sample of 121 patients. These patients were divided into the PAH group (n = 39) and the non-PAH group (n = 82) based on echocardiography results. See Fig. 1 for details on the flowchart.

Table 2. Comparison of laboratory data between PAH group and non-PAH group ($\bar{x} \pm s$).

Variable	PAH group (n = 39)	Non-PAH group (n = 82)	χ^2/t value	<i>p</i> value
WBC ($\times 10^9/L$)	7.12 \pm 1.24	5.33 \pm 0.89	9.067	<0.001
Hemoglobin (g/L)	103.62 \pm 12.89	108.45 \pm 12.23	1.995	0.048
ALB (g/L)	33.12 \pm 4.56	35.87 \pm 5.84	2.587	0.011
Urea nitrogen (mmol/L)	22.24 \pm 2.47	21.18 \pm 2.95	1.942	0.054
Creatinine ($\mu\text{mol/L}$)	804.56 \pm 94.77	809.41 \pm 97.52	0.258	0.797
Uric acid ($\mu\text{mol/L}$)	421.52 \pm 56.23	390.62 \pm 90.45	1.959	0.052
eGFR [$\text{mL}/(\text{min} \cdot 1.73 \text{ m}^2)$]	4.89 \pm 1.33	4.62 \pm 1.41	1.002	0.318
CRP (mg/L)	3.29 \pm 0.88	2.95 \pm 0.97	1.855	0.066
Total cholesterol (mmol/L)	4.65 \pm 1.26	4.71 \pm 1.34	0.235	0.815
Calcium (mmol/L)	2.24 \pm 0.57	2.33 \pm 0.49	0.895	0.373
Phosphate (mmol/L)	1.84 \pm 0.46	1.72 \pm 0.51	1.247	0.215
Ferritin (mg/mL)	201.58 \pm 69.84	205.44 \pm 71.45	0.280	0.780
PTH (mmol/L)	238.91 \pm 74.58	225.63 \pm 80.31	0.869	0.386

PAH, pulmonary arterial hypertension; WBC, white blood cell; ALB, albumin; eGFR, estimated glomerular filtration rate; CRP, C-reactive protein; PTH, parathyroid hormone.

Baseline Characteristics of Study Participants

The general data, including gender, age, and primary renal disease type, were compared between the PAH group and the non-PAH group. There were no statistically significant differences in these variables ($p > 0.05$), as shown in Table 1.

Comparison of Laboratory Data between PAH Group and Non-PAH Group

The WBC count in the PAH group was significantly higher than in the non-PAH group, while the levels of hemoglobin and ALB were significantly lower in the PAH group compared to the non-PAH group ($p < 0.05$). There were no statistically significant differences in other laboratory data between the two groups ($p > 0.05$), as shown in Table 2.

Comparison of Echocardiography and CPET Parameters between PAH Group and Non-PAH Group

The PAH group showed lower values in VO_2 peak (peak oxygen uptake), VO_2 AT (anaerobic threshold oxygen uptake), METspeak (peak metabolic equivalents), WRpeak (peak power load) compared to the non-PAH group, with statistically significant differences ($p < 0.05$). There were no statistically significant differences in other echocardiography and CPET parameters between the two groups ($p > 0.05$), as shown in Table 3.

Multifactorial Logistic Regression Analysis of Factors Influencing the Occurrence of PAH in PD Patients

Using the variables that showed statistically significant differences in the univariate analysis as independent variables, and with the occurrence of PAH in PD patients as the dependent variable (1 = Yes, 0 = No), multifactorial logistic regression analysis was conducted. The results indicated that WBC was an independent

Table 3. Comparison of echocardiography and CPET parameters between PAH group and non-PAH group ($\bar{x} \pm s$).

Variable	PAH group (n = 39)	Non-PAH group (n = 82)	χ^2/t value	<i>p</i> value
Left ventricular ejection fraction (%)	56.44 ± 6.28	57.18 ± 6.59	0.586	0.559
Interventricular septum (mm)	10.05 ± 1.58	10.31 ± 1.74	0.791	0.431
Left ventricular diastolic diameter (mm)	49.42 ± 5.89	48.57 ± 6.32	0.706	0.481
VO ₂ peak [mL (kg·min)]	14.15 ± 1.62	18.23 ± 1.94	11.465	<0.001
VO ₂ AT [mL (kg·min)]	8.44 ± 0.58	10.16 ± 0.76	12.498	<0.001
METSpeak [mL (kg·min)]	3.84 ± 0.62	5.73 ± 1.38	8.157	<0.001
VO ₂ /HRpeak	8.94 ± 2.33	9.06 ± 2.45	0.256	0.799
WRpeak	67.89 ± 13.12	82.15 ± 10.18	6.544	<0.001

CPET, cardiopulmonary exercise testing; VO₂peak, peak oxygen uptake; VO₂AT, anaerobic threshold oxygen uptake; METSpeak, peak metabolic equivalents; VO₂/HRpeak, peak oxygen pulse; WRpeak, peak power load.

Table 4. Multifactorial logistic regression analysis of factors influencing the occurrence of PAH in PD patients.

Factor	β	SE	Wald χ^2	<i>p</i>	OR	95% CI
WBC	0.814	0.256	10.111	<0.001	2.257	1.367–3.728
Hemoglobin	−0.031	0.016	3.771	0.052	0.970	0.940–1.000
ALB	−0.048	0.038	1.615	0.204	0.953	0.884–1.027
VO ₂ peak	−0.149	0.048	9.571	0.002	0.862	0.785–0.947
VO ₂ AT	−0.127	0.055	5.307	0.035	0.881	0.791–0.981
METSpeak	−0.298	0.112	7.099	0.008	0.742	0.596–0.924
WRpeak	−0.217	0.098	4.899	0.041	0.805	0.664–0.975

SE, standard error; OR, odds ratio; CI, confidence interval.

risk factor for PAH in PD patients ($p < 0.05$). VO₂peak, VO₂AT, METSpeak, and WRpeak were identified as protective factors for PAH in PD patients ($p < 0.05$). There was no significant correlation between hemoglobin, ALB, and PAH in PD patients ($p > 0.05$), as shown in Table 4.

ROC Curve Analysis of CPET Parameters for Predicting PAH Development in PD Patients

Using the occurrence of PAH in PD patients as the state variable (1 = Yes, 0 = No) and VO₂peak, VO₂AT, METSpeak, and WRpeak as the test variables, ROC curves were plotted. The results of the ROC curve analysis indicated that the area under the receiver operating characteristic (ROC) curve (AUC) for predicting the occurrence of PAH in PD patients were 0.675 for VO₂peak, 0.651 for VO₂AT, 0.719 for METSpeak, and 0.689 for WRpeak. Among these, METSpeak demonstrated the highest AUC for prediction, as shown in Table 5 and Fig. 2.

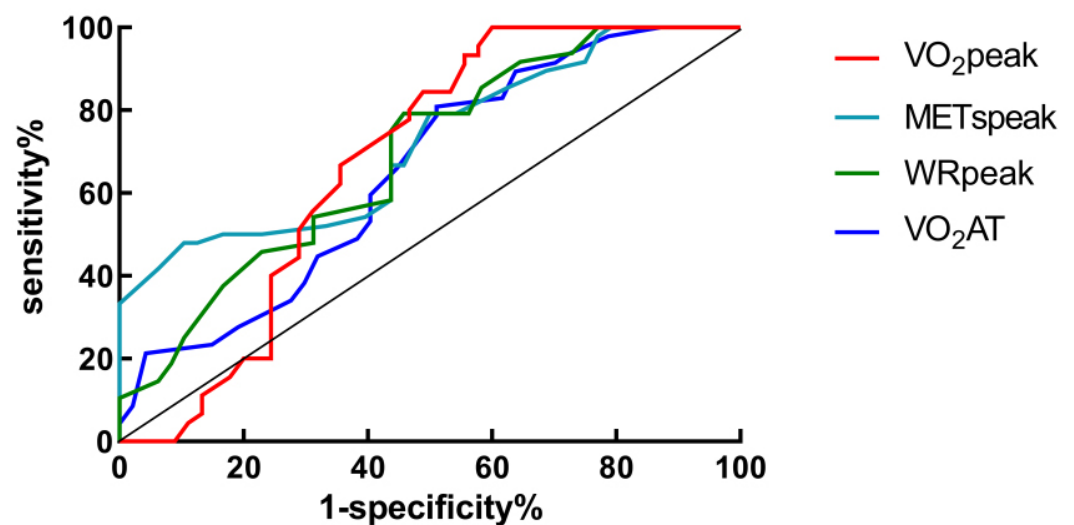
Discussion

The specific pathogenesis of PAH remains unclear. In PD patients, elevated pulmonary artery pressure caused by PAH leads to a sustained increase in right

Table 5. ROC curve analysis of CPET parameters for predicting PAH development in PD patients.

Index	AUC	95% CI	Optimal cutoff	Sensitivity	Specificity
VO ₂ peak	0.675	0.558–0.792	16.3	66.67	64.44
VO ₂ AT	0.651	0.541–0.762	9.1	59.57	55.51
METspeak	0.719	0.618–0.821	4.8	70.74	65.23
WRpeak	0.689	0.583–0.794	71.5	60.33	56.74

AUC, the area under the receiver operating characteristic (ROC) curve.

**Fig. 2.** ROC curve of CPET parameters for predicting PAH development in PD patients.

ventricular load, ultimately resulting in right heart failure or cardiogenic sudden death (Zhang et al, 2020). The continuous increase in pulmonary vascular resistance and pulmonary blood flow are the two main reasons for the development of PAH. Elevated pulmonary vascular resistance is influenced by abnormal pulmonary vascular constriction, which leads to *in-situ* thrombi formation and pulmonary vascular remodeling. These changes cause alterations in pulmonary vascular structure and function. Long-term cardiac compensation results in increased blood volume, which is a key factor contributing to the continuous rise in pulmonary blood volume (Alhwiesh et al, 2022; Song et al, 2023). The pathogenesis of PAH in PD patients is highly complex, with multiple factors influencing pulmonary artery pressure and pulmonary blood flow. Therefore, identifying the risk factors for PAH in PD patients is crucial for the prevention and treatment of this condition.

In this study, we explored the association between CPET parameters and the occurrence of PAH in PD patients and analyzed the predictive value of these parameters for PAH. Using a pulmonary artery pressure ≥ 35 mmHg from echocardiography results as the diagnostic criterion for assessing PAH, patients were categorized into the PAH group and the non-PAH group. CPET data from both groups were collected and analyzed. The results indicated that VO₂peak, VO₂AT, METspeak, and WRpeak levels were significantly lower in the PAH group compared to the non-PAH group, consistent with findings by Tsuboi et al (2017). Previous study has

highlighted a relationship between cardiopulmonary function and the occurrence of PAH in PD patients ([Gadioli et al, 2023](#)).

Peritoneal dialysis involves the infusion of dialysate into the abdominal cavity, which may lead to fluid overload with long-term use. Inadequate fluid removal can result in fluid accumulation in the systemic and pulmonary circulations, increasing pulmonary artery pressure. Additionally, the chemical composition of the dialysate, such as high sodium, high calcium, or acidity, may burden the cardiopulmonary system. Imbalances in the dialysate components can lead to fluid retention or metabolic disturbances, affecting pulmonary artery pressure. Therefore, assessing the cardiopulmonary function of PD patients is important for predicting PAH.

CPET, a comprehensive technique for assessing respiratory and circulatory system function, objectively evaluates cardiopulmonary reserve and exercise tolerance. Study by [Dorken Gallastegi et al \(2022\)](#) has shown that pre-implantation CPET parameters have good predictive value for long-term survival outcomes after left ventricular assist device implantation. Research has found that PD patients may have subclinical cardiopulmonary dysfunction, and reduced CRF in these patients is influenced by both central and peripheral functions. CPET parameters can help analyze the mechanisms of chronic kidney dysfunction and detect subclinical cardiopulmonary abnormalities ([Wu et al, 2022](#)).

In this study, multifactorial logistic regression analysis revealed that WBC was an independent risk factor for PAH in PD patients, while VO_2 peak, VO_2 AT, METspeak, and WRpeak were identified as protective factors. Research by [Walther et al \(2020\)](#) highlighted that dialysis patients frequently experience a systemic state of microinflammation due to factors such as ineffective toxin clearance, stimulation from dialysis procedures and dialysate, and oxidative stress. Inadequate dialysis leading to toxin accumulation can cause gastrointestinal reactions, malnutrition, and increased susceptibility to secondary infections ([Walther et al, 2020](#)). Elevated WBC levels reflect the inflammatory status of the body and have been found to be an important predictive factor for mortality during hospitalization in patients with chronic kidney disease ([Chen et al, 2022](#)).

VO_2 peak, VO_2 AT, METspeak, and WRpeak are crucial CPET parameters that evaluate cardiopulmonary function and reflect the overall health of the cardiopulmonary system. Lower values in these indicators typically suggest poorer cardiopulmonary function, which can increase the risk of developing PAH due to inadequate cardiac output and ventilation when under stress or during exercise ([Andonian et al, 2021](#)). [Tobita et al \(2023\)](#) found a close association between CPET parameters, such as VO_2 peak, VO_2 AT, and METspeak, and impaired exercise tolerance in PAH patients with normal hemodynamics.

In this study, to further evaluate the predictive value of CPET parameters for PAH, ROC curves were plotted, and the AUC values were calculated for each parameter. The results indicated that the AUC for predicting PAH in PD patients were 0.675 for VO_2 peak, 0.651 for VO_2 AT, 0.719 for METspeak, and 0.689 for WRpeak. Among these, METspeak had the highest AUC, suggesting its superior predictive value. METspeak, which refers to the maximum metabolic equivalent achieved during exercise testing, is a key measure of exercise capacity. Previous

research has shown that low METspeak values reflect poor exercise capacity, often associated with inadequate cardiac output and diminished pulmonary ventilation efficiency (Aburub et al, 2020).

Wang et al (2024a) analyzed cardiopulmonary exercise test results in 36 Parkinson's disease patients and 12 healthy controls. They found that Parkinson's patients had significantly lower METspeak levels compared to the healthy controls. Additionally, these patients exhibited sluggish responses in heart rate and systolic blood pressure during exercise testing. Factors such as female gender, older age, symptom fluctuations, advanced disease stages, and high daily activity levels were associated with lower oxygen consumption (Wang et al, 2024a).

This study has several limitations. Firstly, the sample size is relatively small and consists of data from a single-center retrospective analysis, which may introduce some bias and limit the generalizability of the results. This limitation could also contribute to the lower AUC values observed for some CPET parameters. Additionally, PD patients often experience metabolic abnormalities, such as acid-base and electrolyte imbalances, which can affect cardiopulmonary function and potentially influence their performance in exercise tests.

Furthermore, while the study used echocardiography to assess PAH, the gold standard for PAH diagnosis is right heart catheterization. Echocardiography provides indirect measurements of pulmonary artery pressure based on indicators like right ventricular function, pulmonary artery diameter, and hemodynamic patterns. These indirect estimates may introduce errors and affect the accuracy of PAH diagnosis. Future research should focus on expanding the sample size and exploring the specific mechanisms of PAH to better understand the predictive value of CPET parameters and improve diagnostic accuracy.

Conclusion

In conclusion, WBC, and CPET parameters such as VO_{2peak} , VO_{2AT} , METspeak, and WRpeak are linked to the occurrence of PAH in PD patients. Among these, CPET parameters have demonstrated predictive value for PAH, with METspeak showing the highest AUC. Enhancing CPET parameters could potentially improve cardiopulmonary function in PD patients, help reduce the incidence of PAH, and offer valuable guidance for clinical prevention and treatment strategies.

Key Points

- WBC is a significant factor contributing to the development of PAH in PD patients.
- CPET parameters are effective in predicting the occurrence of PAH in PD patients.
- A close association exists between CPET parameters and the occurrence of PAH, highlighting their role in assessing cardiopulmonary function.
- METspeak showed the highest AUC for predicting PAH, indicating its strong predictive value.

Availability of Data and Materials

The data used to support the findings of this study are available from the corresponding author upon request.

Author Contributions

YXX and YZ designed the research. YXX, YZ and XNQ performed the research. YXX, XNQ, YZ, YL and ZCY analyzed the data. YXX and YZ drafted the manuscript. All authors contributed to important editorial changes in the manuscript. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

This study was approved by the medical ethics committee of the Xuzhou Medical University Affiliated Hospital (Ethical batch number: XYFY2021-KL199-01). The entire experimental procedure adhered to the principles of informed consent, with patients or their family members being provided with information about the study, and informed consent was obtained from all study participants.

Acknowledgement

We are grateful to patients participating in this study and to rehabilitation department for their help and cooperation during the study.

Funding

This research received no external funding.

Conflict of Interest

The authors declare no conflict of interest.

References

- Aburub A, Ledger SJ, Sim J, Hunter SM. Cardiopulmonary Function and Aerobic Exercise in Parkinson's: A Systematic Review of the Literature. *Movement Disorders Clinical Practice*. 2020; 7: 599–606. <https://doi.org/10.1002/mdc3.13011>
- Alhwiesh AK, Abdul-Rahman IS, Alshehri A, Alhwiesh A, Elnokeety M, Essam S, et al. The problem of pulmonary arterial hypertension in end-stage renal disease: can peritoneal dialysis be the solution. *BMC Nephrology*. 2022; 23: 386. <https://doi.org/10.1186/s12882-022-02998-y>
- Andonian BJ, Hardy N, Bendelac A, Polys N, Kraus WE. Making Cardiopulmonary Exercise Testing Interpretable for Clinicians. *Current Sports Medicine Reports*. 2021; 20: 545–552. <https://doi.org/10.1249/JSR.0000000000000895>
- Annaiah E, Karanam S, Sharvani N, Singh SB, Vanajakshamma V, Hemalatha M, et al. Pulmonary Artery Hypertension in Patients on Peritoneal Dialysis. *Saudi Journal of Kidney Diseases and Transplantation*. 2021; 32: 280–283. <https://doi.org/10.4103/1319-2442.318543>
- Bech-Hanssen O, Smith JG, Astengo M, Bollano E, Bobbio E, Polte CL, et al. Pulmonary Hypertension Phenotype Can Be Identified in Heart Failure With Reduced Ejection Fraction Using

- Echocardiographic Assessment of Pulmonary Artery Pressure With Supportive Use of Pressure Reflection Variables. *Journal of the American Society of Echocardiography*. 2023; 36: 604–614. <https://doi.org/10.1016/j.echo.2023.01.011>
- Chen J, Li Y, Liu P, Wu H, Su G. A nomogram to predict the in-hospital mortality of patients with congestive heart failure and chronic kidney disease. *ESC Heart Failure*. 2022; 9: 3167–3176. <https://doi.org/10.1002/ehf2.14042>
- Chuasuwana A, Pooripussarakul S, Thakkinstian A, Ingsathit A, Pattanaprateep O. Comparisons of quality of life between patients underwent peritoneal dialysis and hemodialysis: a systematic review and meta-analysis. *Health and Quality of Life Outcomes*. 2020; 18: 191. <https://doi.org/10.1186/s12955-020-01449-2>
- Dewar A, Kass L, Stephens RCM, Tetlow N, Desai T. Heart Rate Recovery Assessed by Cardiopulmonary Exercise Testing in Patients with Cardiovascular Disease: Relationship with Prognosis. *International Journal of Environmental Research and Public Health*. 2023; 20: 4678. <https://doi.org/10.3390/ijerph20064678>
- Dorken Gallastegi A, Ergi GD, Kahraman Ü, Yağmur B, Çınar E, Karapolat H, et al. Prognostic Value of Cardiopulmonary Exercise Test Parameters in Ventricular Assist Device Therapy. *ASAIO Journal*. 2022; 68: 808–813. <https://doi.org/10.1097/MAT.0000000000001571>
- Gadioli LP, Costa FA, Moreira HT, Crescêncio JC, Bertini CQ, Marques F, et al. Use of Cardiopulmonary Exercise Testing to Assess Pulmonary Hypertension in Patients With Rheumatic Mitral Valve Disease: A Comparative Study With Echocardiography. *Current Problems in Cardiology*. 2023; 48: 101230. <https://doi.org/10.1016/j.cpcardiol.2022.101230>
- Guazzi M, Arena R, Halle M, Piepoli MF, Myers J, Lavie CJ. 2016 focused update: clinical recommendations for cardiopulmonary exercise testing data assessment in specific patient populations. *European Heart Journal*. 2018; 39: 1144–1161. <https://doi.org/10.1093/eurheartj/ehw180>
- Han M, Qie R, Shi X, Yang Y, Lu J, Hu F, et al. Cardiorespiratory fitness and mortality from all causes, cardiovascular disease and cancer: dose-response meta-analysis of cohort studies. *British Journal of Sports Medicine*. 2022; 56: 733–739. <https://doi.org/10.1136/bjsports-2021-104876>
- Karkar A, Wilkie M. Peritoneal dialysis in the modern era. *Peritoneal Dialysis International: Journal of the International Society for Peritoneal Dialysis*. 2023; 43: 301–314. <https://doi.org/10.1177/08968608221114211>
- Kirkman DL, Chavez DA. Exercise for chronic kidney disease: effects on vascular and cardiopulmonary function. *American Journal of Physiology. Heart and Circulatory Physiology*. 2024; 326: H138–H147. <https://doi.org/10.1152/ajpheart.00400.2023>
- Kurl S, Hakkarainen P, Voutilainen A, Lönnroos E. Combined effects of maximal oxygen uptake and glucose status on mortality: The Prospective KIHHD cohort study. *Scandinavian Journal of Medicine & Science in Sports*. 2022; 32: 913–923. <https://doi.org/10.1111/sms.14135>
- Li Y, Shang W, Lu Q, Zhang B, Ren Y, Sun Y, et al. Prevalence of pulmonary hypertension in peritoneal dialysis patients: a meta-analysis. *International Urology and Nephrology*. 2019; 51: 175–180. <https://doi.org/10.1007/s11255-018-2017-4>
- Maron BA. Revised Definition of Pulmonary Hypertension and Approach to Management: A Clinical Primer. *Journal of the American Heart Association*. 2023; 12: e029024. <https://doi.org/10.1161/JAHA.122.029024>
- Orihuela O, de Jesus Ventura M, Carmona-Ruiz HA, Santos-Martinez LE, Sánchez AR, Paniagua R. Pulmonary Hypertension in Patients Starting Peritoneal Dialysis. *Archives of Medical Research*. 2020; 51: 254–260. <https://doi.org/10.1016/j.arcmed.2020.02.004>
- Rroji M, Cafka M, Seferi S, Seiti J, Barbullushi M, Goda A. The potential effect of cardiac function on pulmonary hypertension, other risk factors, and its impact on survival in dialysis patients. *International Urology and Nephrology*. 2021; 53: 343–351. <https://doi.org/10.1007/s11255-020-02655-z>
- Schoenberg NC, Argula RG, Klings ES, Wilson KC, Farber HW. Prevalence and Mortality of Pulmonary Hypertension in ESRD: A Systematic Review and Meta-analysis. *Lung*. 2020; 198: 535–545. <https://doi.org/10.1007/s00408-020-00355-0>

- Song L, Quan ZL, Zhao LY, Cui DM, Zhong M, Zhou LF, et al. Impact of pulmonary hypertension on arteriovenous fistula failure of hemodialysis patients: A 10 years follow-up cohort study. *The Journal of Vascular Access*. 2023; 24: 261–270. <https://doi.org/10.1177/11297298211027408>
- Tobita K, Goda A, Teruya K, Nishida Y, Takeuchi K, Kikuchi H, et al. Exercise Capacity and Ventilatory Efficiency in Patients With Pulmonary Arterial Hypertension. *Journal of the American Heart Association*. 2023; 12: e026890. <https://doi.org/10.1161/JAHA.122.026890>
- Tsuboi Y, Tanaka H, Nishio R, Sawa T, Terashita D, Nakayama K, et al. Associations of Exercise Tolerance With Hemodynamic Parameters for Pulmonary Arterial Hypertension and for Chronic Thromboembolic Pulmonary Hypertension. *Journal of Cardiopulmonary Rehabilitation and Prevention*. 2017; 37: 341–346. <https://doi.org/10.1097/HCR.0000000000000257>
- Walther CP, Nambi V, Hanania NA, Navaneethan SD. Diagnosis and Management of Pulmonary Hypertension in Patients With CKD. *American Journal of Kidney Diseases*. 2020; 75: 935–945. <https://doi.org/10.1053/j.ajkd.2019.12.005>
- Wang K, Cheng H, Yang B, Liu D, Maria M, Wu Q, et al. Assessment of cardiorespiratory fitness in Chinese patients with early to mid-stage Parkinson's disease. *The International Journal of Neuroscience*. 2024a. (online ahead of print) <https://doi.org/10.1080/00207454.2024.2377140>
- Wang L, Mei F, Min M, He X, Luo L, Ma Y. Adoption of the cardiopulmonary exercise test in the exercise ability and cardiopulmonary function rehabilitation of coronary artery disease (CAD) patients. *BMC Cardiovascular Disorders*. 2024b; 24: 313. <https://doi.org/10.1186/s12872-024-03958-0>
- Wu X, Zhang Y, Wang F, Xiang J. Cardiopulmonary exercise testing to observe subclinical abnormalities in cardiopulmonary function in patients undergoing peritoneal dialysis. *Clinical Physiology and Functional Imaging*. 2022; 42: 269–277. <https://doi.org/10.1111/cpf.12756>
- Zhang X, Zhao W, Ma X, Li Y, Shang H, Zhang J, et al. Prognostic value of pulmonary hypertension in pre-dialysis chronic kidney disease patients. *International Urology and Nephrology*. 2020; 52: 2329–2336. <https://doi.org/10.1007/s11255-020-02589-6>