

• 临床研究 •

# 脉冲振荡技术参数联合模型在老年慢性阻塞性肺疾病中的诊断价值分析

王佳月<sup>1,2</sup>, 王艳丽<sup>1</sup>, 王正霞<sup>1</sup>, 陈中琦<sup>1</sup>, 黄 茂<sup>1</sup>, 孙培莉<sup>1\*</sup>, 吴桢珍<sup>1\*</sup>

<sup>1</sup>南京医科大学第一附属医院呼吸与危重症医学科, 江苏 南京 210029; <sup>2</sup>太仓市第一人民医院急诊科, 江苏 苏州 215400

**[摘要]** 目的: 探讨脉冲振荡技术(impulse oscillometry system, IOS)在老年慢性阻塞性肺疾病(chronic obstructive pulmonary disease, COPD)患者中的诊断价值。方法: 采取单中心观察性研究, 纳入2019年9月—2023年8月于南京医科大学第一附属医院就诊的670例老年COPD患者及101例健康对照者。所有受试者均先后完成IOS及肺量测定, 收集其人口学特征、IOS参数及肺功能指标。IOS检测严格遵循国际与中国指南, 记录5、10、20 Hz时的呼吸系统阻力(R5、R10、R20)和电抗(X5、X10、X20)、R5和R20之差(R5-R20)、共振频率(frequency of resonance, Fres)等指标, 并进行Z分数标准化。采用Spearman相关性、广义线性模型(Gamma分布, Log连接)及分位数回归( $\tau=0.5$ )评估IOS参数与肺功能指标的关系, 通过ROC曲线评估诊断效能。结果: 与对照组相比, COPD组R5、R5-R20、Fres增高, X5降低( $P$ 均 $<0.001$ )。相关性分析显示, R5、R5-R20、Fres与第1秒用力呼气容积占预计值百分比(FEV<sub>1</sub>%pred)呈负相关(R5:  $r=-0.500$ ,  $P<0.001$ ; R5-R20:  $r=-0.584$ ,  $P<0.001$ ; Fres:  $r=-0.546$ ,  $P<0.001$ ), X5、X20与FEV<sub>1</sub>%pred呈正相关(X5:  $r=0.609$ ,  $P<0.001$ ; X20:  $r=0.529$ ,  $P<0.001$ ), 校正年龄、性别、BMI及吸烟指数后, GOLD 2、3、4级患者的R5-R20较GOLD 1级分别增加34.3%、119.2%、189.2%( $P$ 均 $<0.001$ ); R5分别增加15.2%、49.3%和66.6%( $P$ 均 $<0.001$ ); Fres分别增加16.0%、42.1%和64.6%( $P$ 均 $<0.001$ ); X5和X20逐级降低, X5系数为-0.047、-0.186和-0.328( $P$ 均 $<0.001$ ); X20系数依次为-0.025、-0.059和-0.089( $P$ 均 $<0.001$ )。联合Fres、R5、R20、X5、X20的多参数模型诊断效能提升, AUC达0.803(95%CI: 0.761~0.845), 灵敏度为59%, 特异度为88%, Nagelkerke  $R^2$ 为38%。结论: 脉冲振荡技术可有效评估老年COPD患者的气道阻力和肺弹性特性, 多参数联合诊断模型具有一定诊断效能, 可作为老年COPD的重要辅助诊断工具。

**[关键词]** 慢性阻塞性肺疾病; 脉冲振荡技术; 肺量测定法; 小气道功能障碍; 诊断效能

**[中图分类号]** R736.1

**[文献标志码]** A

**[文章编号]** 1007-4368(2026)09-1323-08

**doi:** 10.7655/NYDXBNSN260558

## Diagnostic value of a combined model of impulse oscillometry parameters in elderly patients with COPD

WANG Jiayue<sup>1,2</sup>, WANG Yanli<sup>1</sup>, WANG Zhengxia<sup>1</sup>, CHEN Zhongqi<sup>1</sup>, HUANG Mao<sup>1</sup>, SUN Peili<sup>1\*</sup>, WU Zhenzhen<sup>1\*</sup>

<sup>1</sup>Department of Respiratory and Critical Care Medicine, the First Affiliated Hospital of Nanjing Medical University, Nanjing 210029; <sup>2</sup>Department of Emergency Medicine, the First People's Hospital of Taicang, Suzhu 215400, China

**[Abstract]** **Objective:** To investigate the diagnostic value of impulse oscillometry (IOS) in older patients with chronic obstructive pulmonary disease (COPD). **Methods:** This single-center observational study enrolled 670 older patients with COPD and 101 healthy controls who attended the First Affiliated Hospital of Nanjing Medical University between September 2019 and August 2023. All participants underwent IOS followed by spirometry. Demographic characteristics, IOS parameters, and spirometric indices were collected. IOS measurements were performed in strict accordance with international and Chinese guidelines. Respiratory system resistance at 5, 10, and 20 Hz (R5, R10, and R20), respiratory system reactance at 5, 10, and 20 Hz (X5, X10, and X20), the difference between R5 and R20 (R5 - R20), and resonant frequency (Fres) were recorded and converted to Z scores. Spearman correlation analysis, generalized linear models with a gamma distribution and log-link function, and median quantile regression ( $\tau=0.5$ )

**[基金项目]** 国家科技重大专项(2023ZD0506300); 国家自然科学基金(82300033)

\*通信作者(Corresponding author), E-mail: plisun9419@njmu.edu.cn(ORCID: 0009-0001-7966-5886); wzz\_0809@163.com(ORCID: 0009-0002-9435-1882)

were used to evaluate the associations between IOS parameters and spirometric indices. Receiver operating characteristic (ROC) curve analysis was performed to assess diagnostic performance. **Results:** Compared with healthy controls, patients with COPD had significantly higher R5, R5-R20, and Fres and significantly lower X5 values (all  $P < 0.001$ ). R5, R5-R20, and Fres were negatively correlated with the percentage of predicted forced expiratory volume in 1 second (FEV<sub>1</sub>% predicted; R5:  $r = -0.500$ ,  $P < 0.001$ ; R5-R20:  $r = -0.584$ ,  $P < 0.001$ ; Fres:  $r = -0.546$ ,  $P < 0.001$ ). In contrast, X5 and X20 were positively correlated with FEV<sub>1</sub>% predicted (X5:  $r = 0.609$ ,  $P < 0.001$ ; X20:  $r = 0.529$ ,  $P < 0.001$ ). After adjustment for age, sex, body mass index, and smoking index, R5-R20 was 34.3%, 119.2%, and 189.2% higher in patients with global initiative for chronic obstructive lung disease (GOLD) grades 2, 3, and 4, respectively, than in those with GOLD grade 1 (all  $P < 0.001$ ). The corresponding increases in R5 were 15.2%, 49.3%, and 66.6% (all  $P < 0.001$ ), whereas Fres increased by 16.0%, 42.1%, and 64.6%, respectively (all  $P < 0.001$ ). X5 and X20 progressively decreased with increasing GOLD grade. The regression coefficients for X5 were  $-0.047$ ,  $-0.186$ , and  $-0.328$  for GOLD grades 2, 3, and 4, respectively, and those for X20 were  $-0.025$ ,  $-0.059$ , and  $-0.089$ , respectively (all  $P < 0.001$ ). A multivariable model combining Fres, R5, R20, X5, and X20 demonstrated improved diagnostic performance, with an area under the ROC curve of 0.803 (95% confidence interval: 0.761-0.845), a sensitivity of 59%, a specificity of 88%, and a Nagelkerke  $R^2$  of 38%. **Conclusion:** IOS can effectively characterize airway resistance and the elastic properties of the respiratory system in older patients with COPD. A diagnostic model combining multiple IOS parameters showed moderate diagnostic performance and may serve as a useful adjunctive tool for the diagnosis of COPD in older adults.

**[Key words]** chronic obstructive pulmonary disease; impulse oscillometry; spirometry; small airway dysfunction; diagnostic performance

[J Nanjing Med Univ, 2026, 46(09): 1323-1330]

慢性阻塞性肺疾病(chronic obstructive pulmonary disease, COPD)是一种异质性疾病,病理改变涵盖肺气肿、气道炎症、黏液纤毛功能障碍、细支气管炎和小气道结构改变,临床以气流受限持续性进行性加重为主要特征。2021年全球COPD病死率为45.5/10万,位于死亡原因的第4位,并且呈上升趋势<sup>[1]</sup>。我国COPD患病率随年龄增长而升高,60~69岁为21.2%,70岁以上老年人的患病率高达35.5%<sup>[2-3]</sup>。老年人是COPD的高发人群,但该群体的诊断不足问题尤为突出,一方面,COPD早期表现缺乏特异性,常被归于年老体衰,另一方面,现行COPD的诊断依赖于肺量检测,此项检查需要患者用力呼气,对于年老体弱、肺功能严重受损或有认知功能障碍的患者难度较大。关于老年人肺功能检测质量的研究显示,仅30%的患者能完成符合欧洲呼吸学会/美国胸科学会质量标准的肺功能检测<sup>[4]</sup>。此外,老年患者往往合并多种疾病(如高血压、冠心病、牙周病等),其症状和COPD部分重合从而干扰临床诊断<sup>[5]</sup>。尽管吸入支气管舒张剂后1秒率,即第1秒用力呼气容积(forced expiratory volume in 1 second, FEV<sub>1</sub>)占用力肺活量(forced vital capacity, FVC)的百分比(FEV<sub>1</sub>/FVC)<0.7仍是COPD的诊断标准,但此标准在老年人群中易导致过度诊断<sup>[3]</sup>,因为正常老年人的FEV<sub>1</sub>/FVC比值也会随着年龄增长

而自然下降。因此,探索更适合老年患者的COPD诊断标准尤为重要。

脉冲振荡法(impulse oscillometry system, IOS)<sup>[6]</sup>是一种无创评估大小气道阻力的技术,其原理为仪器发出脉冲波叠加在正常潮式呼吸上通过大小气道传播后反射,由压力和流量传感器接受,再通过信号过滤将压力和流量的合成信号与呼吸模式分离。患者正常潮式呼吸就能完成检查,无需用力吹气,适用于儿童以及虚弱或无法进行肺活量测定的老年人。多项研究表明,吸入较低剂量的醋甲胆碱,FEV<sub>1</sub>出现变化之前,IOS阻抗参数就已增加,提示IOS可能比肺量测定更敏感<sup>[6-7]</sup>。然而,IOS在老年COPD人群中的应用尚缺乏大规模临床研究数据支持。目前关于IOS在老年COPD患者中应用的大样本研究较少,且多局限于单一参数的评价,缺乏多参数联合诊断模型的系统评估。本研究基于670例老年COPD患者的大样本数据,系统评估IOS参数在老年COPD中的诊断价值,并构建多参数联合诊断模型,系统探讨IOS在老年COPD患者中的临床应用价值。

## 1 对象和方法

### 1.1 对象

本研究是一项单中心观察性研究,连续选取2019年9月—2023年8月于南京医科大学第一附属

医院行肺功能检查的670例老年COPD患者并收集其临床资料,包括性别、年龄、身高、体重、吸烟史、慢性病史。入组患者需同时完成肺量和脉冲振荡检查,按纳入标准及排除标准筛检。本研究经南京医科大学伦理委员会批准(伦理号:2024-SR-843)。

纳入标准:①根据全球慢性阻塞性肺疾病倡议组织(global initiative for chronic obstructive lung disease, GOLD)2019明确诊断COPD的患者;②年龄 $\geq 60$ 岁;③肺功能质控标准A级;④所有患者均在完成IOS检测休息2~3 min后完成肺计量检测。排除标准:①合并肺恶性肿瘤;②患有间质性肺疾病、睡眠呼吸暂停等其他呼吸系统疾病(哮喘除外);③存在胸廓畸形和胸水;④有肺部手术史;⑤合并其他显著增加病死率的疾病;⑥完成IOS后未能继续完成肺量计测定;⑦一般资料数据不全。同时纳入年龄 $\geq 60$ 岁、无慢性呼吸系统疾病史、肺通气功能检查正常的健康老年人作为对照组。

## 1.2 方法

IOS:检查操作严格遵循欧洲呼吸学会<sup>[6]</sup>及中国肺功能脉冲振荡指南<sup>[8]</sup>。为规避用力呼气对气道张力的潜在影响,IOS均在肺活量测定之前进行。设备扬声器产生的压力振荡通过吹嘴叠加到受试者自主潮气呼吸上,持续30~45 s,频率范围为5~35 Hz。受试者取坐姿,佩戴鼻夹,检查者以手轻压其脸颊,以最大限度减少脸颊振动和漏气的影响。结果以呼吸系统总阻力(respiratory resistance system, Rrs)和呼吸系统总电抗(respiratory reactance system, Xrs)呈现,阻抗指气道对气流的阻碍能力,包括气道的阻力和弹性。而电抗主要反映气道的弹性和惯性特性。记录5、10、20 Hz时的呼吸系统阻力(R5、R10、R20)和电抗(X5、X10、X20)、R5和R20之间的差异(R5~R20)、共振频率(frequency of resonance, Fres)及各参数占预计值百分比。

各参数定义如下:阻抗参数中,R5反映呼吸系统总气道阻力。R20反映中心气道阻力。R5~R20反映阻力的频率依赖性,即Rrs在振荡频率逐渐增高时的变化,是评估外周气道阻力的敏感指标。健康人中Rrs无频率依赖性,即R5~R20趋于零,而在外周气道阻塞时,R5增高,R20增高不明显,Rrs随频率增高而降低,即R5~R20显著升高。R5~R10亦为频率依赖性阻力指标,与R5-R20意义相近,也可用于评估小气道功能障碍。

电抗参数中,X5代表外周气道及肺实质的弹性阻力,反映肺顺应性。X5一般为负值,绝对值越大

表示弹性阻力越大。X10临床意义与X5相似,但对小气道变化的敏感性略低于X5。X20(20 Hz时的电抗)由于频率较高,惯性阻力所占比重增大,与X5相比对小气道功能障碍的敏感性降低。惯性阻力和弹性阻力的方向相反,Fres为当两者大小相等、互相抵消时,Xrs为零的频率,一般在5~10 Hz之间,气道阻塞性疾病因X5的下降而导致Fres增加。

为了消除人体测量学因素的影响,数据分析中采用标准化的Z分数,Rrs及X5的Z值=(实测值-预计值)/RSD,RSD参考全球肺功能倡议。判定标准为:R5、R10、R20的Z值 $> 1.64$ 为异常,X5的Z值 $< -1.64$ 为异常<sup>[9]</sup>。

肺量测定法:根据美国胸科学会ERS指南,受试者吸入沙丁胺醇后进行肺量测定。记录FEV<sub>1</sub>、FVC、FEV<sub>1</sub>/FVC、最大中期呼气流量(FEF<sub>25~75</sub>)、残气量(residual volume, RV)、肺总量(total lung capacity, TLC)、RV/TLC的实测值及占预测值的百分比。预测方程基于对4~80岁中国人正常肺活量测定值的大型研究<sup>[10]</sup>。

## 1.3 统计学方法

采用SPSS27.0统计分析软件进行数据分析,计数资料采用百分数表示,组间比较采用 $\chi^2$ 检验。经Shapiro-Wilk检验,本研究中所有计量资料均不符合正态分布,故以中位数(四分位数)[ $M(P_{25}, P_{75})$ ]表示,两组间比较(如健康对照组与COPD组)采用Mann-Whitney U检验。采用Spearman相关性分析来确定IOS参数与肺通气功能指标之间的相关性。采用广义线性模型(Gamma分布、Log连接)分析阻力参数(R5、R20、Fres)随COPD严重程度(GOLD分级)的变化趋势,结果以 $\exp(\beta)$ 及其95%CI表示。因电抗参数(X5、X20)含负值且呈偏态分布,采用分位数回归( $\tau=0.5$ ,中位数回归),Bootstrap法(1 000次重抽样)估计95%CI。多因素模型均以GOLD 1级为参照,校正年龄、性别、BMI及吸烟指数等混杂因素。绘制受试者操作特征(receiver operating characteristic, ROC)曲线以表示真阳性率(敏感性)与假阳性率(特异性)之间的关系。 $P < 0.05$ 为差异有统计学意义。

## 2 结果

### 2.1 人口统计学特征及肺功能测量指标

本研究共纳入670例老年COPD患者及101例健康对照者,COPD组与健康对照组在性别构成差异上无统计学意义,但COPD组患者的年龄更高、体



重指数(body mass index, BMI)更低、吸烟指数更高,符合疾病危险因素特征(表1)。

与健康对照组相比,COPD患者外周气道阻力(R5~R20)及总气道阻力(R5)显著增加,电抗参数X5显著降低( $P$ 均 $<0.001$ ),小气道功能障碍指标(MMEF%pred)显著恶化(表2)。为消除个体差异,进一步比较两组异常Z值的发生率,结果显示COPD组R5异常发生率高达59.7%,显著高于健康对照组的21.8%,提示R5是区分两组的最敏感指标。此外,两组X5异常发生率均超过70%,表明大部分老年人的外周气道弹性阻力增加(图1)。以上结果表明,IOS可检测COPD患者的小气道病变和肺力学改变。

2.2 IOS参数与FEV<sub>1</sub>/FVC及FEV<sub>1</sub>%pred的相关性

由于10 Hz与5 Hz的阻抗参数存在严重共线性,后续分析未纳入R10、X10。Spearman相关性分析显示,反映总气道阻力、外周气道阻力及共振频

率的指标R5、R5-R20、Fres与FEV<sub>1</sub>%pred呈中等负相关(R5:  $r=-0.500, P<0.001$ ; R5~R20:  $r=-0.584, P<0.001$ ; Fres:  $r=-0.546, P<0.001$ ),反映中心气道阻力的R20相关性较弱( $r=-0.226, P<0.001$ )。反映外周及中央气道弹性阻力的X5、X20与FEV<sub>1</sub>%pred呈中等正相关(X5:  $r=0.609, P<0.001$ ; X20:  $r=0.529, P<0.001$ )。此外,IOS参数(Fres、R5、X5)亦与小气道功能障碍(MMEF%pred)、气体潴留(RV/TLC)密切相关(表3)。

2.3 IOS参数与COPD严重程度的关联及诊断效能分析

经广义线性模型及分位数回归校正年龄、性别、BMI及吸烟史后,Fres、R5及R5~R20随GOLD分级升高而递增,其中外周阻力R5~R20递增幅度较为突出。与GOLD 1级相比,GOLD 2、3、4级患者的R5~R20分别增加34.3%、119.2%、189.2%; R5分别

表1 健康对照组与COPD组人口统计学特征

| Variable                                        | Healthy control group( $n=101$ ) | COPD group ( $n=670$ ) | $Z(\chi^2)$ | $P$ value |
|-------------------------------------------------|----------------------------------|------------------------|-------------|-----------|
| Male[ $n(\%)$ ]                                 | 98(97.03)                        | 650(97.01)             | $<0.001$    | 0.994     |
| Age[years, $M(P_{25}, P_{75})$ ]                | 67.00(64.00, 71.00)              | 70.00(65.00, 74.00)    | -3.256      | 0.001     |
| BMI[kg/m <sup>2</sup> , $M(P_{25}, P_{75})$ ]   | 24.28(22.27, 26.28)              | 23.23(20.92, 25.41)    | -3.213      | 0.001     |
| Smoking index[pack-years, $M(P_{25}, P_{75})$ ] | 30.00(20.00, 35.00)              | 35.00(25.00, 40.00)    | -5.46       | $<0.001$  |

表2 健康对照组与COPD组IOS参数与肺量测定指标比较

Table 2 Comparison of IOS parameters and spirometry indicators between healthy controls and COPD patients  
[ $M(P_{25}, P_{75})$ ]

| Parameter                        | Healthy control group( $n=101$ ) | COPD group( $n=670$ ) | $Z$     | $P$      |
|----------------------------------|----------------------------------|-----------------------|---------|----------|
| Respiratory impedance parameters |                                  |                       |         |          |
| R5[cmH <sub>2</sub> O/(L·s)]     | 2.98(2.44, 3.86)                 | 4.27(3.23, 5.37)*     | -8.197  | $<0.001$ |
| R10[cmH <sub>2</sub> O/(L·s)]    | 2.68(2.17, 3.39)                 | 3.15(2.55, 3.84)*     | -4.606  | $<0.001$ |
| R20[cmH <sub>2</sub> O/(L·s)]    | 2.38(1.97, 2.82)                 | 2.66(2.24, 3.18)*     | -4.090  | $<0.001$ |
| R5-R20[cmH <sub>2</sub> O/(L·s)] | 0.59(0.28, 1.00)                 | 1.48(0.84, 2.27)*     | -9.386  | $<0.001$ |
| Fres(Hz)                         | 15.12(13.03, 17.90)              | 20.33(16.32, 23.65)*  | -8.561  | $<0.001$ |
| X5[cmH <sub>2</sub> O/(L·s)]     | -0.98(-1.24, -0.59)              | -1.85(-3.21, -1.06)*  | -8.361  | $<0.001$ |
| X10[cmH <sub>2</sub> O/(L·s)]    | -0.23(-0.54, -0.06)              | -1.03(-1.83, -0.45)*  | -9.852  | $<0.001$ |
| X20[cmH <sub>2</sub> O/(L·s)]    | 0.43(0.17, 0.61)                 | -0.02(-0.45, 0.28)*   | -8.705  | $<0.001$ |
| Spirometry parameters            |                                  |                       |         |          |
| FEV <sub>1</sub> (L)             | 2.84(2.58, 3.14)                 | 1.57(1.09, 2.00)*     | -14.966 | $<0.001$ |
| FEV <sub>1</sub> %pred           | 103.40(96.25, 111.60)            | 59.05(43.20, 75.25)*  | -15.575 | $<0.001$ |
| FVC(L)                           | 3.50(3.26, 3.90)                 | 2.69(2.16, 3.15)*     | -11.212 | $<0.001$ |
| FVC%pred                         | 99.50(92.80, 108.80)             | 78.00(64.88, 91.23)*  | -11.659 | $<0.001$ |
| FEV <sub>1</sub> /FVC(%)         | 79.61(77.44, 82.55)              | 58.74(50.18, 65.71)*  | -16.216 | $<0.001$ |
| MMEF% pred                       | 80.10(70.70, 96.30)              | 19.40(12.80, 30.48)*  | -16.209 | $<0.001$ |

\* indicates a statistically significant difference( $P<0.001$ ) between groups by Mann-Whitney  $U$  test.



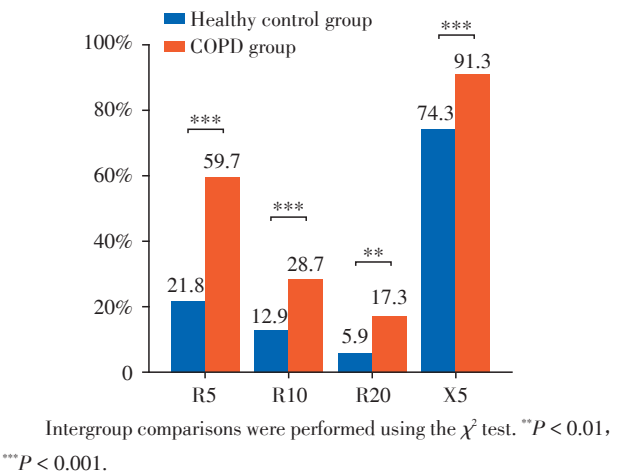


图1 健康对照组与COPD组呼吸阻抗参数的异常比例对比  
Figure 1 Comparison of abnormal proportions of respiratory impedance parameters between the healthy controls and COPD patients

增加 15.2%、49.3%和 66.6% ( $P$  均 $<0.001$ ); R20 分别增加 6.6% ( $P=0.051$ )、18.6%和 16.2% ( $P$  均 $<0.01$ ); Fres 分别增加 16.0%、42.1%和 64.6% ( $P$  均 $<0.001$ )。电抗参数则随 GOLD 分级升高而降低(负值增大): X5 系数依次为  $-0.047$ 、 $-0.186$  和  $-0.328$  ( $P$  均 $<0.001$ ); X20 系数依次为  $-0.025$ 、 $-0.059$  和  $-0.089$  ( $P$  均 $<0.001$ ), 提示肺弹性阻力随疾病严重程度进行性加重(表4)。

ROC 曲线分析显示, 单一 IOS 参数中 X20、Fres、X5 及 R5 均表现出较高的诊断效能。联合 Fres、R5、R20、X5、X20 构建多参数诊断模型进一步提高了诊断特异性, AUC 为 0.803 (95%CI: 0.761~0.845), 灵敏度为 59%, 特异度为 88%, Nagelkerke  $R^2$  为 38% (表5, 图2)。

表4 多因素校正后 GOLD

Table 4 Impact of multi-factor adjustment on

| Parameter              | GOLD 2                      |
|------------------------|-----------------------------|
| $\exp(\beta)$ (95% CI) |                             |
| R5                     | 1.152(1.067–1.243)***       |
| R20                    | 1.066(1.000–1.136)          |
| R5-R20                 | 1.343(1.174–1.537)***       |
| Fres                   | 1.160(1.094–1.231)***       |
| B(95%CI)               |                             |
| X5                     | −0.047(−0.074 to −0.020)*** |
| X20                    | −0.025(−0.036 to −0.014)*** |

Generalized linear models (Gamma distribution with log link) were used for Fres, R5 and R20, where exp( $\beta$ ) represents fold change. Median regression (quantile regression at  $\tau=0.5$ ) with 1 000 bootstrap resamples was used for X5 and X20, where “B” represents median change. All models were adjusted for age, sex, BMI and smoking index, with GOLD 1 as the reference group. Significance markers: \* $P < 0.05$ , \*\* $P < 0.01$ , \*\*\* $P < 0.001$ . Values in parentheses are 95% confidence intervals (exponentiated for resistance parameters; original bootstrap CIs for reactance parameters).

表3 IOS与肺通气功能指标的相关性分析  
Table 3 Correlation analysis between IOS parameters and pulmonary ventilation function indicators ( $r$ )

| Parameter | FEV <sub>1</sub> %pred | FEV <sub>1</sub> /FVC | MMEF%pred  | RV/TLC     |
|-----------|------------------------|-----------------------|------------|------------|
| R5        | $-0.500^*$             | $-0.445^*$            | $-0.504^*$ | $0.332^*$  |
| R20       | $-0.226^*$             | $-0.184^*$            | $-0.231^*$ | $0.171^*$  |
| R5~R20    | $-0.584^*$             | $-0.529^*$            | $-0.588^*$ | $0.383^*$  |
| Fres      | $-0.546^*$             | $-0.504^*$            | $-0.540^*$ | $0.358^*$  |
| X5        | $0.609^*$              | $0.541^*$             | $0.614^*$  | $-0.409^*$ |
| X20       | $0.529^*$              | $0.487^*$             | $0.524^*$  | $-0.339^*$ |

Spearman rank correlation analysis was used. All correlation coefficients were statistically significant. \* $P < 0.001$ . FEV<sub>1</sub>%pred: forced expiratory volume in the first second as percentage of predicted value; MMEF%pred: maximal mid-expiratory flow as percentage of predicted value; RV/TLC: ratio of residual volume to total lung capacity.

3 讨论

肺活量测定是COPD诊断与严重程度分级的常用标准。然而, 该技术主要评估大气道的通气功能, 对于COPD病理生理进程中最早发生且最为核心的小气道病变的评估存在局限性。小气道功能障碍可早于FEV<sub>1</sub>/FVC下降出现, 且与疾病进展、急性加重风险增加及生活质量下降相关<sup>[11]</sup>。Cosío等<sup>[12]</sup>发现, 在40岁以上人群中将近四分之一的中老年人有呼吸道症状和肺结构异常, 但常规肺量测定结果仍处于正常范围。老年COPD患者因症状不典型、合并疾病多、难以配合用力呼气, 肺量检查失败率高<sup>[4, 13]</sup>。上述问题共同构成IOS的潜在应用场景——无需用力呼吸, 通过R5、R20、Fres等参数直接量化小气道功能。

表5 呼吸阻抗参数AUC值与临床诊断效能分级表

| Table 5 AUC values of respiratory impedance parameters and grading of clinical diagnostic efficacy |                    |              |             |             |
|----------------------------------------------------------------------------------------------------|--------------------|--------------|-------------|-------------|
| Parameter                                                                                          | AUC(95%CI)         | Youden index | Sensitivity | Specificity |
| Combined                                                                                           | 0.803(0.761–0.845) | 0.47         | 0.59        | 0.88        |
| R5-R20                                                                                             | 0.790(0.747–0.833) | 0.44         | 0.59        | 0.85        |
| X20                                                                                                | 0.768(0.719–0.818) | 0.42         | 0.68        | 0.74        |
| Fres                                                                                               | 0.765(0.718–0.813) | 0.41         | 0.68        | 0.73        |
| X5                                                                                                 | 0.758(0.714–0.801) | 0.45         | 0.66        | 0.79        |
| R5                                                                                                 | 0.755(0.708–0.801) | 0.42         | 0.72        | 0.70        |
| R20                                                                                                | 0.627(0.570–0.685) | 0.21         | 0.55        | 0.66        |

AUC: Area under the curve; 95% CI: 95% confidence interval; Youden index=Sensitivity+Specificity-1. Parameters with AUC>0.7 have clinical reference value, but should be combined to improve diagnostic performance.

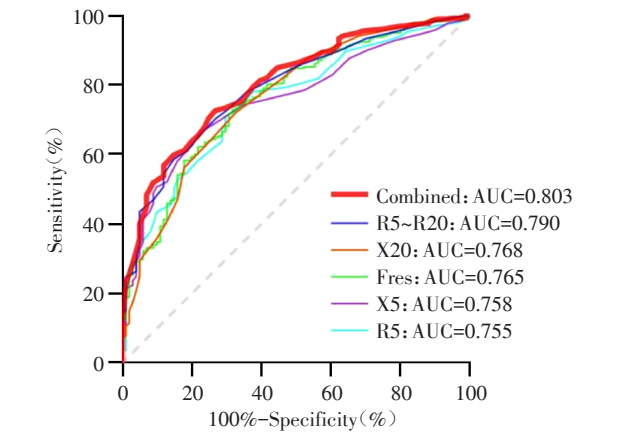


图2 基于脉冲振荡技术的ROC曲线分析  
Figure 2 ROC curve analysis based on impulse oscillometry

基于670例老年COPD患者的大样本数据,本研究系统评估了IOS在该人群中的辅助诊断价值。主要发现:老年COPD患者呈现R5~R20增高、X5负值增大、Fres右移的阻力与弹性失衡特征;IOS参数与FEV<sub>1</sub>%pred、MMEF%pred、呈中等强度相关,且独立于年龄、BMI、吸烟指数;联合R5、R20、Fres、X5、X20的多参数模型显著优于单一参数。

直径<2 mm的小气道是气体交换的关键场所,易受炎症、黏液分泌和肺泡损伤影响,是COPD进展的核心环节<sup>[14]</sup>。GOLD 1级患者的R5~R20已显著升高而FEV<sub>1</sub>%pred仍在正常范围,提示IOS对小气道病变的早期识别能力优于肺量测定。两组X5异常发生率均超过70%,提示肺弹性减退在老年人中较为常见,临床解读X5宜采用年龄匹配的参考值。

Fres、R5、R5~R20与FEV<sub>1</sub>%pred呈中等负相关,X5与FEV<sub>1</sub>%pred呈正相关,效应量与纳入39项研究的Meta分析结果高度一致<sup>[15]</sup>,支持气道阻力增加与肺弹性减退是肺通气功能下降的关键病理机

制。IOS参数与MMEF%pred、亦呈中等强度相关,提示其能同时反映小气道功能障碍,与既往研究结论相符<sup>[16–17]</sup>。

单个IOS参数如R5~R20等均表现出较高的诊断效能。本研究构建的多参数联合模型将AUC提升至0.803(灵敏度59%、特异度88%),该联合模型以较高的特异度为特征,而灵敏度稍低,提示其更适用于辅助诊断而非筛查,临床应用时应结合患者临床症状及危险因素综合判断。在一定程度上提供了老年COPD群体大样本多参数联合诊断的参考依据。此外,IOS操作简便、重复性好<sup>[18–19]</sup>,近期研究证实IOS参数与急性加重风险、FEV<sub>1</sub>快速下降相关<sup>[20–21]</sup>,该模型目前主要用于辅助诊断,其在老年COPD早期筛查与病情监测中的量化价值有待进一步研究验证。

本研究为单中心观察性设计,健康对照组与COPD组在年龄、BMI及吸烟指数等基线特征上存在一定差异,但已通过多因素回归进行校正,结论仍具稳健性。联合模型AUC为0.803,提示临床应用时需结合症状综合判断。本研究以男性为主,结果外推至女性时需谨慎。未来可通过多中心外部验证进一步评估模型的普适性,并建立针对中国老年人群的IOS参考值数据库。

综上,IOS联合诊断模型对老年COPD具有良好诊断效能,可作为肺量的重要补充,尤其适用于无法配合常规用力呼气检查的老年患者。

本研究证实,脉冲振荡技术能够无创、有效地评估老年COPD患者的气道阻力和肺弹性特性,对识别小气道功能障碍具有一定敏感性。联合多个IOS参数的诊断模型表现出的较好诊断效能,可能成为老年COPD,特别是无法完成高质量肺量检查患者的一种辅助诊断工具,具有广阔的临床应用前景。

利益冲突声明:

所有作者声明无利益冲突。

Conflict of Interests:

All authors declare no conflict of interests.

作者贡献声明:

王佳月负责初稿撰写与修订,数据收集与分析;王艳丽、王正霞、陈中琦、黄茂、吴桢珍负责肺功能质控与数据核对;孙培莉、吴桢珍负责研究设计与论文审阅。

Author's Contributions:

Wang Jiayue was responsible for the drafting and revision of the manuscript, as well as data collection and analysis. Wang Yanli, Wang Zhengxia, Chen Zhongqi, Huang Mao, and Wu Zhenzhen were responsible for pulmonary function quality control and data verification. Sun Peili and Wu Zhenzhen were responsible for study design and manuscript review.

[参考文献]

[1] VOLLSET S E, ABABNEH H S, ABATE Y H, et al. GBD 2021 Forecasting Collaborators. Burden of disease scenarios for 204 countries and territories, 2022-2050: a forecasting analysis for the Global Burden of Disease Study 2021[J]. Lancet, 2024, 403(10440): 2204-2256

[2] 基本公共卫生服务项目基层慢阻肺病防治管理办公室,国家慢性呼吸疾病防治办公室,国家呼吸医学中心,等. 国家基层慢性阻塞性肺疾病防治及管理实施指南(2025)[J]. 中华结核和呼吸杂志, 2026, 49(01): 11-28

Basic Public Health Service Project Primary COPD Prevention and Management Office, National Chronic Respiratory Disease Prevention and Control Office, National Respiratory Medicine Center, et al. National primary chronic obstructive pulmonary disease prevention and management implementation guide (2025) [J]. Chinese Journal of Tuberculosis and Respiratory Diseases, 2026, 49(01): 11-28

[3] 中国老年医学学会呼吸病学分会慢性阻塞性肺疾病学组. 中国老年慢性阻塞性肺疾病临床诊治实践指南 [J]. 中华结核和呼吸杂志, 2020, 43(02): 100-119

Chronic Obstructive Pulmonary Disease Group, Respiratory Branch of Chinese Geriatrics Society. Clinical practice guideline for diagnosis and management of chronic obstructive pulmonary disease in elderly patients [J]. Chinese Journal of Tuberculosis and Respiratory Diseases, 2020, 43(02): 100-119

[4] CENGIZ S K, SAVAS I K, COSKUN E, et al. Conformity of spirometric tests with acceptability criteria and assessment of confounding factors in routine clinical practice [J]. Ann Thorac Med, 2025, 20(3): 176-182

[5] 中华医学学会呼吸病学分会肺功能学组. 成人肺功能检

查技术进展及临床应用推荐指南(2025版)[J]. 中华肺部疾病杂志(电子版), 2025, 18(2): 197-212

Pulmonary Function Group, Respiratory Branch of Chinese Medical Association. Recommended guidelines for technical advances and clinical application of adult pulmonary function testing (2025 edition) [J]. Chinese Journal of Pulmonary Diseases (Electronic Edition), 2025, 18(2): 197-212

[6] KING G G, BATES J, BERGER K I, et al. Technical standards for respiratory oscillometry [J]. Eur Respir J, 2020, 55(2): 1900753

[7] RINGBAEK T, FRØLUND L, MORTENSEN J, et al. Comparing changes in FEV<sub>1</sub> and impulse oscillometry parameters following methacholine challenge testing: physiological correlates, clinical markers, and pulmonary symptoms [J]. J Clin Med, 2026, 15(5): 2025

[8] 中国医师协会呼吸医师分会肺功能与临床呼吸生理工作委员会,中华医学会呼吸病学分会肺功能学组,中国老年医学会呼吸分会肺功能学组. 肺功能检查技术规范——脉冲振荡技术检查 [J]. 中华结核和呼吸杂志, 2022, 45(10): 960-969

Committee on Pulmonary Function and Clinical Respiratory Physiology, Respiratory Physician Branch of Chinese Medical Doctor Association; Pulmonary Function Group, Respiratory Branch of Chinese Medical Association; Pulmonary Function Group, Respiratory Branch of Chinese Geriatric Society. Technical standards for pulmonary function tests: impulse oscillometry [J]. Chinese Journal of Tuberculosis and Respiratory Diseases, 2022, 45(10): 960-969

[9] LIANG X, ZHENG J, GAO Y, et al. Clinical application of oscillometry in respiratory diseases: an impulse oscillometry registry [J]. ERJ Open Res, 2022, 8(4): 00080-2022

[10] JIAN W, GAO Y, HAO C, et al. Reference values for spirometry in Chinese aged 4-80 years [J]. J Thorac Dis, 2017, 9(11): 4538-4549

[11] HUANG S, WU F, DENG Z, et al. Comparing spirometry, impulse oscillometry with computed tomography for assessing small airway dysfunction in subjects with and without chronic obstructive pulmonary disease [J]. BMC Pulm Med, 2025, 25(1): 45

[12] COSÍO B G, CASANOVA C, SOLER-CATALUÑA J J, et al. Unravelling young COPD and pre-COPD in the general population [J]. ERJ Open Res, 2023, 9(1): 00334-2022

[13] LI Y, SU K C, HSIAO Y H, et al. The impact of age and disease entity on small airway dysfunction in obstructive airway diseases [J]. Int J Chron Obstruct Pulmon Dis,



- 2025, 20: 821–830
- [14] Global Initiative for Chronic Obstructive Lung Disease (GOLD) Global Strategy for Prevention, Diagnosis and Management of COPD: 2026 Report [EB/OL] (2025-11-11) [2026-06-03] <https://goldcopd.org/2026-gold-report/>, 2026
- [15] PENG J, LI X, ZHOU H, et al. Clinical value of impulse oscillometry in chronic obstructive pulmonary disease: a systematic review and meta-analysis [J]. *Respiration*, 2025, 104(2): 100–109
- [16] TAMURA K, SHIRAI T, HIRAI K, et al. Mucus plugs and small airway dysfunction in asthma, COPD, and asthma-COPD overlap [J]. *Allergy Asthma Immunol Res*, 2022, 14(2): 196–209
- [17] KLITGAARD A, LØKKE A, HILBERG O. Impulse oscillometry as a diagnostic test for pulmonary emphysema in a clinical setting [J]. *J Clin Med*, 2023, 12(4): 1547
- [18] XU J, SUN X, ZHU H, et al. Long-term variability of impulse oscillometry and spirometry in stable COPD and asthma [J]. *Respir Res*, 2022, 23(1): 262
- [19] LU L, TANG G, WAN Q, et al. Long-term variability of impulse oscillometry defined small airway dysfunction in participants with and without chronic obstructive pulmonary disease [J]. *BMJ Open Respir Res*, 2026, 13(1): e003918
- [20] FÄRDIG M, LINGMAN K, LISSPERS K, et al. Peripheral airway function and disease burden in COPD [J]. *ERJ Open Res*, 2025, 11(4): 01078–2024
- [21] HUANG Y, ZHANG X, WANG J, et al. Role of impulse oscillometry in chronic obstructive pulmonary disease and asthma-chronic obstructive pulmonary disease overlap [J]. *Clin Transl Allergy*, 2025, 15(4): e70057
- (收稿: 2026-05-06; 修回: 2026-07-03; 录用: 2026-07-06)  
(本文编辑: 唐震)

(上接第 1322 页)

- of human neural stem cells requires the amyloid precursor protein [J]. *Sci Adv*, 2023, 9(24): eadd5002
- [14] SONG P W, HAN T Y, WU Z M, et al. Transplantation of neural stem cells loaded in an IGF-1 bioactive supramolecular nanofiber hydrogel for the effective treatment of spinal cord injury [J]. *Adv Sci*, 2024, 11(17): e2306577
- [15] HAYASHI Y, LIN H T, LEE C C, et al. Effects of neural stem cell transplantation in Alzheimer's disease models [J]. *J Biomed Sci*, 2020, 27(1): 29
- [16] LIU Y F, LIU H T, CHANG C, et al. Stereotactically intracerebral transplantation of neural stem cells for ischemic stroke attenuated inflammatory responses and promoted neurogenesis: an experimental study with monkeys [J]. *Int J Surg*, 2024, 110(9): 5417–5433
- [17] RAO J, LI H, ZHANG H, et al. Periplaneta Americana (L.) extract activates the ERK/CREB/BDNF pathway to promote post-stroke neuroregeneration and recovery of neurological functions in rats [J]. *J Ethnopharmacol*, 2024, 321: 117400
- [18] SNYDER E Y, DEITCHER D L, WALSH C, et al. Multipotent neural cell lines can engraft and participate in development of mouse cerebellum [J]. *Cell*, 1992, 68(1): 33–51
- [19] STALLINGS N R, O'NEAL M A, HU J, et al. Long-term normalization of calcineurin activity in model mice rescues Pin1 and attenuates Alzheimer's phenotypes without blocking peripheral T cell IL-2 response [J]. *Alzheimers Res Ther*, 2023, 15(1): 179
- [20] WANG S W, GAO C, ZHENG Y M, et al. Current applications and future perspective of CRISPR/Cas9 gene editing in cancer [J]. *Mol Cancer*, 2022, 21(1): 57
- [21] FRANGOUL H, ALTSHULER D, CAPPELLINI M D, et al. CRISPR-Cas9 gene editing for sickle cell disease and  $\beta$ -thalassemia [J]. *N Engl J Med*, 2021, 384(3): 252–260
- [22] RUSTIGHI A, ZANNINI A, CAMPANER E, et al. PIN1 in breast development and cancer: a clinical perspective [J]. *Cell Death Differ*, 2017, 24(2): 200–211
- [23] LA R S. Diagnostic, prognostic, and predictive role of Ki67 proliferative index in neuroendocrine and endocrine neoplasms: past, present, and future [J]. *Endocr Pathol*. 2023, 34(1): 79–97
- [24] HUANG X, WANG Y J, LI Q S, et al. Coupling of stemness maintenance with cell cycle control in stem cells [J]. *Front Cell Dev Biol*, 2025, 13: 1693489
- [25] HAARWOOD D S L, PEDERSEN V, BAGER N S, et al. Glioblastoma cells increase expression of notch signaling and synaptic genes within infiltrated brain tissue [J]. *Nat Commun*, 2024, 15(1): 7857
- (收稿: 2025-12-26; 修回: 2026-03-22; 录用: 2026-03-24)  
(本文编辑: 戴玉娟)