



基于时空电阻抗成像的腭裂言语呼吸功能评估： 可解释性机器学习研究*

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摘要 目的 评估时空电阻抗断层成像 (spatiotemporal electrical impedance tomography, ST-EIT) 在言语发声任务下, 能否有效捕捉并区分腭裂 (cleft palate, CP) 患者与正常对照 (normal control, NC) 的言语呼吸功能特征。方法 本研究纳入 75 名受试者 (CP 组 37 例, NC 组 38 例)。在标准化发声任务中, 同步采集电阻抗断层成像 (electrical impedance tomography, EIT) 图像与口鼻气流信号, 构建涵盖时间、气流与空间维度的三域特征, 采用曼-惠特尼 U 检验 (Mann-Whitney U test) 比较组间差异。基于肺量计法 (spirometry)、鼻音计 (nasometry) 及 ST-EIT 等多源数据, 分别训练极端梯度提升 (extreme gradient boosting, XGBoost) 分类模型, 采用 5 折交叉验证评估性能, 并引入 Shapley 加法性解释 (Shapley additive explanations, SHAP) 方法进行特征贡献分析。结果 CP 组呈现显著的呼吸表型差异。时间域中, 吸/呼相位时长均显著缩短 ($P < 0.001$), 吸/呼时间比显著升高; 气流域中, 呼气期平均气流与峰值气流显著增强, 吸气期无明显差异; 空间域中, 感兴趣区 (region of interest, ROI) 1 和 4 的潮气阻抗变化 (tidal impedance variation, TIV) 显著升高, ROI2 显著降低, 全局不均一性 (global inhomogeneity, GI) 较低, 通气中心 (center of ventilation, CoV) 呈轻度升高。ST-EIT 模型分类性能最佳, 曲线下面积 (area under the curve, AUC) 达 0.915, 准确率优于单一肺功能检测或鼻音计检测。SHAP 结果表明, 时空特征对分类决策贡献最大。结论 ST-EIT 技术能有效揭示 CP 患者言语呼吸功能在时间-气流-空间三域的特异性改变, 为床旁筛查、康复评估及随访监测提供了优于常规检测的客观量化依据。

关键词 电阻抗断层成像, 腭裂, 言语呼吸, 时空特征, 机器学习, 可解释性分析

中图分类号 TH772

DOI: 10.3724/j.pibb.2025.0462

CSTR: 32369.14.pibb.20250462

唇腭裂 (cleft lip and/or palate, CL/P) 是最常见的先天性颅颌面畸形之一, 全球发病率约为每 700~1 000 名新生儿中 1 例, 其发生与遗传及环境因素的交互作用密切相关^[1-2]。腭裂 (cleft palate, CP) 言语障碍的核心病理为腭咽闭合不全 (velopharyngeal insufficiency, VPI), 即发声与吞咽时软腭不能有效封闭鼻腔通路, 口鼻腔气流分隔受损^[3-4]。除语音清晰度下降外, VPI 还可能伴随异常呼吸模式与通气分布改变, 提示“呼吸-言语”耦合的生理环节受到破坏^[5]。

尽管接受了规范手术, 仍有相当比例的患儿持续存在言语功能障碍 (speech sound disorder,

SSD) 与言语发育迟缓^[6-7]。此外, 中耳炎反复、听力下降及相关行为问题亦常见, 进一步加重沟通障碍并降低生活质量^[8]。临床上, 鼻音计 (nasometry) 以鼻声比例量化鼻音化程度, 电子鼻咽镜 (nasopharyngoscopy) 可直视腭咽运动, 但二者均存在间接性强、依赖受试者配合与操作者经

* 国家自然科学基金 (62501288), 中国博士后科学基金 (2025M771376, 2025M771364), 陕西省科技计划 (2025GH-YBXM-007) 和江苏省科技计划专项资金 (BZ2024036) 资助项目。

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收稿日期: 2025-10-27, 接受日期: 2026-01-09

验、缺乏高时间分辨的动态量化等局限，难以满足客观、连续监测需求^[9-10]。

近年来，功能成像为言语障碍评估提供了新视角。磁共振成像（magnetic resonance imaging, MRI）有助于描绘软腭与咽壁运动及腭咽闭合模式，但受分辨率、成本与便利性限制^[11]。超声适用于舌体与吞咽评估，但成像质量与穿透深度有限，无法覆盖腭咽与胸腔深部结构的整体协同^[12]。电阻抗断层成像（electrical impedance tomography, EIT）作为无创、无辐射、具有高时间分辨率的功能成像技术，已经广泛应用于呼吸监测、运动评估及慢病管理等领域^[13-15]。现有EIT研究多聚焦平静或用力呼吸，以整体不均匀性（global inhomogeneity, GI）与通气中心（center of ventilation, CoV）等指标表征通气分布^[16]。然而，大多基于单一相位（尤其是吸气相），对呼气相的时序与分布特征关注不足^[17]。需要强调的是，在言语与发声过程中，呼气是关键驱动力，气流的稳定性及其在胸内的时空分布直接决定发音质量^[18]。仅依赖吸气相评估难以全面反映CP人群的言语呼吸异常。

基于此，本研究首次提出在言语情境下应用时

空电阻抗断层成像（spatiotemporal electrical impedance tomography, ST-EIT），获取双相呼吸的肺通气时空分布信息，并通过可解释性机器学习量化多域特征对CP判别的贡献。我们假设：与常规肺量计法（spirometry）与鼻音计相比，ST-EIT能够揭示更具判别力的时间-气流-空间三域特征，为CP人群的床旁筛查、康复干预与随访监测提供客观、量化证据。

1 方法

1.1 受试者

本研究经南京医科大学伦理委员会批准（批件号：南医大伦审（2023）248号），遵循《赫尔辛基宣言》^[19]。所有受试者或其法定监护人于入组前签署书面知情同意书。

共招募CP患者与健康志愿者各40名（图1），因不符合入组标准、存在呼吸系统疾病病史、资料不全或EIT电极带贴附不良等原因排除部分个体，最终纳入CP组37例、对照（normal control, NC）组38例。年龄以中位数〔四分位距〕表示，其他变量以均值±标准差表示。

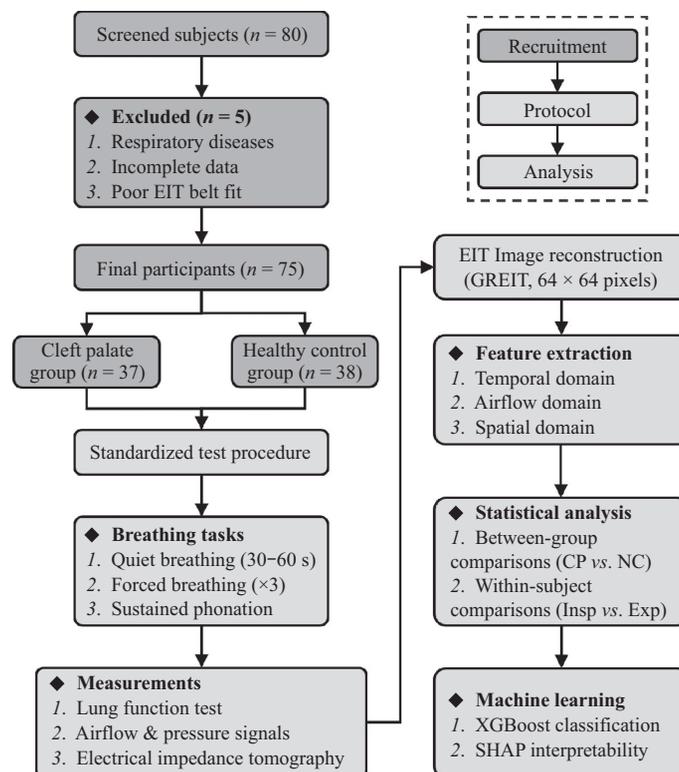


Fig. 1 Participant recruitment and group allocation

Display the screening, exclusion reasons, and final cohorts: cleft palate (CP, n=37) and normal controls (NC, n=38).

CP组 ($n=37$): 女性10例、男性27例; 年龄24.00 [18.50, 27.00] 岁; 身高 (168.44 ± 7.73) cm; 身体质量指数 (body mass index, BMI) (21.34 ± 3.36) kg/m^2 。纳入标准: 临床确诊并存在VPI相关言语功能障碍^[20]。排除标准: 急、慢性呼吸系统疾病史; 认知障碍或听力损失; EIT电极带无法有效贴附胸壁。

正常对照 (normal control, NC) 组 ($n=38$): 健康志愿者; 女性13例、男性25例; 年龄24.00 [22.00, 26.00] 岁; 身高 (172.08 ± 6.61) cm; BMI (22.83 ± 2.54) kg/m^2 。该组在年龄和BMI方面与CP组匹配, 均无CP、言语障碍及呼吸疾病史^[21]。

受试者在标准化条件下完成实验 (图2): 端坐、胸部挺直; 依次进行30~60 s平静呼吸监测、3次用力呼吸以及按预设音节表的持续发声任务; 同步采集EIT与气流/气压信号。随后在捏鼻条件下完成肺功能检测与肺活量测定, 各进行3次取均值, 以保证可靠性与可重复性。

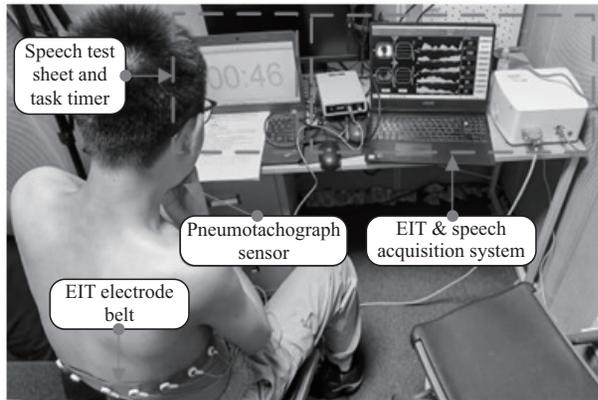


Fig. 2 Experimental setup with labeled components

The setup includes an EIT electrode belt placed around the thorax, a pneumotachograph sensor for airflow and pressure measurement, a speech test sheet used for phonation tasks, a task timer displayed on the screen, and an EIT-speech acquisition system with real-time signal display.

1.2 采集系统与图像重建

本研究采用自研胸阻抗成像系统, 在胸廓第4~5肋间平面放置一圈柔性电极带, 共16个电极, 等距环绕胸壁^[22]。采集过程中, 受试者保持端坐位, 电极层高度覆盖肺部通气区域。

采用相邻驱动与相邻测量的顺序激励模式, 每帧依次完成16对电流注入和208通道电压测量。激励为正弦交流恒流源, 电流幅值约为2 mA、频率100 kHz, 符合EIT临床应用的安全标准。系统采

样帧率设为20 Hz, 可充分捕捉平静呼吸及持续发声任务中的快速通气变化。

以平静呼吸末期的平均帧作为参考帧, 计算各时间点相对阻抗增量。前向模型基于成人胸廓二维有限元网格构建, 电极接触阻抗采用均一边界条件。图像重建采用GREIT (graz consensus reconstruction algorithm for EIT) 算法, 输出矩阵大小为 64×64 像素, 并采用吉洪诺夫 (Tikhonov) 正则化以平衡空间分辨率与噪声抑制, 正则化参数 $\lambda = 0.05$ 通过预实验调节确定^[23]。

1.3 数据分析

1.3.1 数据预处理与重建

所有EIT与气流/气压信号按图3流程离线处理。在16电极相邻驱动与测量模式下, 以20 Hz帧率采集边界电压信号, 并采用GREIT算法将每帧数据重建为 64×64 像素的相对阻抗图像, 随后进行基线漂移校正及吸/呼相位配准, 以降低体动伪影与相位错配。

为便于区域分析, 本研究在重建平面中定义了4个象限感兴趣区 (regions of interest, ROI): ROI1/ROI2分别对应右前/左前肺区, ROI3/ROI4分别对应右后/左后肺区。图像坐标系约定为: 图像上方为腹侧, 下方为背侧, 图像左侧对应受试者右侧、右侧对应受试者左侧。依据该分区计算各象限潮气阻抗变化及相关时空指标。

1.3.2 相位分割与特征提取

将每个呼吸周期分割为吸气 (inspiration, Insp) 与呼气 (expiration, Exp), 并将对应相位的EIT特征集分别记为Insp-EIT与Exp-EIT, 逐像素计算阻抗变化并生成通气功能图像^[24-25]。如表1所示, 按三域提取以下指标:

a. 时间域。相位时长 (phase duration, tPhase)、达峰时间比 (time to peak flow ratio, tPXF/tX)、达峰容积比 (volume at peak flow ratio, vPXF/vX)、40%容积时间比 (time to 40% of tidal volume ratio, z40)、时间常数 (time constant, Tau) 及吸呼时间比 (inspiratory-to-expiratory time ratio, TI/TE)。

b. 气流域。平均流量 (mean flow, MeanFlow)、峰值流量 (peak flow, PeakFlow)、特定容积瞬时流量 (instantaneous flow at 25%/50%/75% of tidal volume, Flow25/50/75) 及25%~75%容积平均流量 (mean flow between 25% and 75% of tidal volume, Flow25-75)。

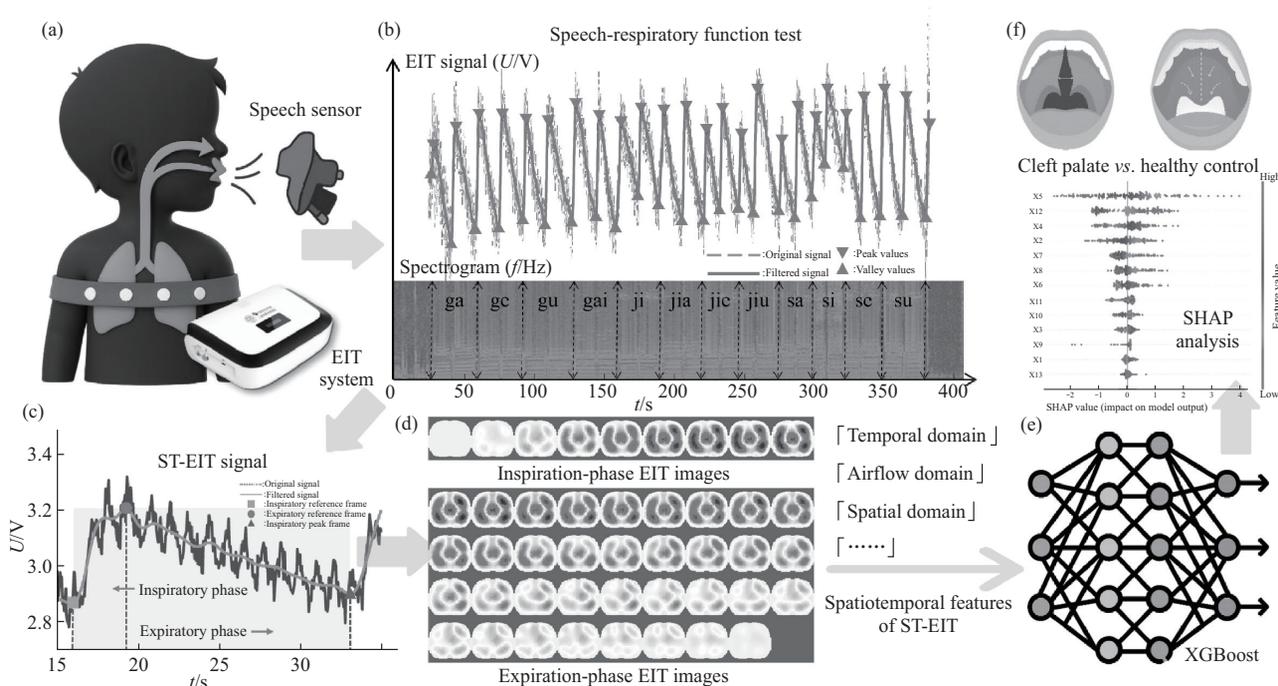


Fig. 3 ST-EIT workflow for speech-respiratory assessment in cleft palate

(a) Synchronous acquisition with EIT and pneumotachograph during sustained phonation. (b) Image reconstruction, baseline correction, and inspiratory/expiratory phase segmentation. (c) Feature extraction across temporal, airflow, and spatial domains, computed at end-inspiration and end-expiration. (d) Representative ST-EIT maps. (e-f) XGBoost classification with SHAP for domain- and parameter-level interpretability. EIT images were reconstructed on a 64×64 matrix from a 16-electrode belt placed at the 4th–5th intercostal level. ROI 1–4 correspond to right-anterior, left-anterior, right-posterior, and left-posterior lung quadrants, respectively. SHAP values quantify the contribution of each feature to the model output and are dimensionless.

c. 空间域。全局潮气阻抗变化 (global tidal impedance variation, TIV_Global)、感兴趣区潮气阻抗变化 (regional tidal impedance variation,

TIV_ROI1-4)、全局不均一性 (global inhomogeneity, GI) 及通气中心 (center of ventilation, CoV)。

Table 1 ST-EIT-derived inspiratory and expiratory parameters organized into temporal-airflow-spatial domains

Category	Inspiration (Insp)	Expiration (Exp)
Temporal domain	Insp_tPhase: inspiratory time; Insp_tPIF/tI: time to peak inspiratory flow/total inspiratory time; Insp_vPIF/vI: inspired volume at peak inspiratory flow/inspiratory tidal volume; Insp_z40: time to 40% of inspiratory tidal volume/total inspiratory time; Insp_Tau: phase time constant from the mid-volume segment (25%→75% of inspiratory volume) using a single-exponential fit	Exp_tPhase: expiratory time; Exp_tPEF/tE: time to peak expiratory flow/total expiratory time; Exp_vPEF/vE: expired volume at peak expiratory flow / expiratory tidal volume; Exp_z40: time to 40% of expiratory tidal volume / total expiratory time; Exp_Tau: phase time constant from the mid-volume segment (75%→25% of expiratory volume) using a single-exponential fit. TI/TE: inspiratory time/ expiratory time
Airflow domain	Insp_MeanFlow: mean inspiratory flow; Insp_PeakFlow: peak inspiratory flow; Insp_Flow25/50/75: instantaneous flow at 25%/50%/75% of inspiratory tidal volume; Insp_Flow25-75: average flow between 25% and 75% of inspiratory tidal volume	Exp_MeanFlow: mean expiratory flow; Exp_PeakFlow: peak expiratory flow; Exp_Flow25/50/75: instantaneous flow at 25%/50%/75% of expiratory tidal volume; Exp_Flow25-75: average flow between 25% and 75% of expiratory tidal volume
Spatial domain	Insp_TIV_Global: global tidal impedance variation (TIV) during inspiration; Insp_TIV_ROI1-4: regional TIV fractions in four quadrants; Insp_GI: global inhomogeneity at end-inspiration; Insp_CoV: center of ventilation at end-inspiration	Exp_TIV_Global: global TIV during expiration; Exp_TIV_ROI1-4: regional TIV fractions in four quadrants; Exp_GI: global inhomogeneity at end-expiration; Exp_CoV: center of ventilation at end-expiration

1.3.3 语音任务同步与可视化

将EIT信号与连续发声片段 (“ga-ge-gu-gai-ji-jia-jie-jiu-sa-si-se-su”) 逐段同步, 提取与言语呼吸相关的时空通气图像^[26]。

1.3.4 统计学分析

连续变量按分布特征以中位数或均值±标准差表示。组间比较 (CP vs. NC) 采用双侧 Mann-Whitney U 检验。在显著性检验的基础上, 进一步报告效应量 r 以量化组间差异强度; 当同一类型指标涉及多重比较时, 采用 Bonferroni 方法进行校正^[27]。以校正后 $P < 0.05$ 作为统计学显著性判定标准。

1.3.5 机器学习与可解释性

分别基于鼻音计、肺量计法、吸气相 EIT (inspiratory EIT, Insp-EIT)、呼气相 EIT (expiratory EIT, Exp-EIT) 与时空 EIT (spatiotemporal EIT, ST-EIT) 构建特征矩阵, 训练极端梯度提升 (extreme gradient boosting, XGBoost) 分类器并进行分层 5 折交叉验证^[28]。采用 Shapley 加性解释 (Shapley additive explanations, SHAP) 方法进行可解释性分析, 获得全局与个体

的特征贡献, 并汇总域级比例用于结果解读^[29]。

2 结果与讨论

2.1 受试者基线特征与肺功能结果

共纳入 75 例受试者 (CP 组: $n=37$; NC 组: $n=38$)。两组中位年龄均为 24 岁 ($P=0.488$)。与 CP 组相比, NC 组身高与 BMI 略高 (分别 $P=0.036$ 、 $P=0.041$)。肺功能方面, CP 组肺活量 (VC) 与用力肺活量 (FVC) 较低 (分别 $P < 0.001$ 、 $P=0.044$)。其余指标, 包括第 1 秒用力呼气容积 (forced expiratory volume in the first second, FEV1)、呼气峰值流量 (peak expiratory flow, PEF)、FEV1/FVC 比值及中末段用力呼气流量 (forced expiratory flow, FEF25、FEF50、FEF75、FEF25-75), 两组相近 (均 $P \geq 0.177$) (表 2)。

CP 组 VC 和 FVC 的降低可能与其长期的呼吸模式异常、气道发育受限或胸廓顺应性差等因素相关, 提示 CP 患者存在轻度的肺容量限制。尽管两组在 FEV1、FEV1/FVC 等指标上相似, 但 CP 组在气流和肺容量方面的变化提示其潜在的呼吸功能调整需求。

Table 2 Baseline characteristics and spirometry in participants with cleft palate and normal control

Module	Metric	CP ($n=37$)	NC ($n=38$)	<i>P</i> -value
Baseline	Age/year	24.00 [18.50, 27.00]	24.00 [22.00, 26.00]	0.488
	Height/cm	168.44±7.73	172.08±6.61	0.036
	BMI/(kg·m ⁻²)	21.34±3.36	22.83±2.54	0.041
Lung Function	VC/L	3.22±1.31	4.21±0.94	<0.001
	FVC/L	3.72±0.95	4.20±1.03	0.044
	FEV1/L	2.55±1.10	2.64±0.86	0.692
	PEF/(L·s ⁻¹)	3.03 [1.79, 4.29]	3.38 [2.36, 4.27]	0.534
	FEV1/FVC	0.81 [0.52, 0.98]	0.68 [0.47, 0.88]	0.177
	FEF25/(L·s ⁻¹)	2.92±1.57	3.09±1.58	0.660
	FEF50/(L·s ⁻¹)	2.64±1.48	2.59±1.12	0.854
	FEF75/(L·s ⁻¹)	1.97±1.16	1.81±0.68	0.495
	FEF25-75/(L·s ⁻¹)	2.53±1.43	2.44±1.02	0.756

Data are mean ± SD unless indicated; age, PEF, and FEV1/FVC are median [IQR]. Two-sided *P* values were obtained using Welch's *t* test or the Mann-Whitney U test, as appropriate. Abbreviations: VC, vital capacity; FVC, forced vital capacity; FEV1, forced expiratory volume in 1 s; PEF, peak expiratory flow; FEV1/FVC, FEV1-to-FVC ratio; FEF25/50/75, forced expiratory flow at 25%/50%/75% of FVC; FEF25-75, mean forced expiratory flow from 25%–75% of FVC; CP, cleft palate; NC, normal control.

2.2 鼻音计结果

在/g/、/j/、/s/三组音节中, 两组鼻音度评分指数 (nasalance score index, NSI) 差异均无统计学意义 (均 $P \geq 0.521$)。与 CP 组相比, NC 组的口腔

得分 (oral score, OS) 及口腔得分指数 (oral score index, OSI) 在/g/ (OS: $P=0.013$; OSI: $P=0.018$)、/j/ (OS: $P=0.003$; OSI: $P=0.006$) 和/s/ (OS: $P=0.007$; OSI: $P=0.006$) 均显著更高; 跨

音节总体均值亦呈相同趋势 (OS: $P=0.006$; OSI: $P=0.008$) (表3)。

从结果来看, 虽然两组在NSI上差异不显著, 但在OS及OSI上, NC组普遍表现较好。CP组的OSI明显较低, 尤其在/g/、/j/和/s/音节的发音中, 可能与其言语功能的异常或发音结构的不同有关。

这些差异可能反映了CP患者在发音过程中口腔气流的分布与控制存在不同, 导致了更高的鼻腔共鸣, 进而影响了整体的口腔发音。整体来看, NC组在发音的控制和清晰度方面优于CP组, 说明NC在口腔发音上有更好的协调性和更低的NSI。

Table 3 Nasalance outcomes in participants with cleft palate and normal control

Syllable	Metric	CP ($n=37$)	NC ($n=38$)	P -value
/g/ga-ge-gu-gai	NSI	30.95 [21.44, 52.17]	29.47 [16.19, 59.54]	0.638
	OS	52.32 [35.05, 84.95]	97.62 [48.87, 174.94]	0.013
	OSI	21.39 [12.73, 31.52]	40.75 [18.85, 63.78]	0.018
/j/ji-jia-jie-jiu	NSI	33.69 [21.61, 55.02]	30.65 [18.81, 56.41]	0.587
	OS	46.29 [23.84, 82.56]	94.20 [48.26, 165.87]	0.003
	OSI	20.81 [11.62, 35.09]	42.90 [21.14, 67.18]	0.006
/s/sa-si-se-su	NSI	38.58 [25.79, 56.46]	31.33 [18.58, 58.91]	0.592
	OS	55.83 [31.38, 85.31]	98.08 [48.06, 175.09]	0.007
	OSI	23.00 [13.56, 32.08]	40.58 [19.96, 79.34]	0.006
Overall Mean (all syllables)	NSI	35.86 [23.15, 53.74]	30.90 [17.62, 59.30]	0.521
	OS	50.39 [29.32, 85.21]	96.28 [48.54, 174.46]	0.006
	OSI	21.85 [11.98, 34.64]	41.52 [20.14, 74.87]	0.008

Data are presented as median [IQR]. Two-sided P values were calculated with the Mann-Whitney U test. Abbreviations: NSI, nasalance score index; OS, oral score; OSI, oral score index; CP, cleft palate; NC, normal control.

2.3 时间域异质性

基于ST-EIT的时间域指标见图4。与NC组相比, CP组的吸气相tPhase显著较短 (1.60 [1.40, 2.05] vs 1.85 [1.60, 2.35]), $P<0.001$, 效应量 $r=0.241$), 提示CP组可能存在较短的呼吸周期或更快速的呼吸模式。在呼气相, CP组的tPhase时间明显低于NC组 (2.45 [1.70, 4.35] vs 3.95 [2.80, 6.55]), $P<0.001$, 效应量 $r=0.291$), 这可能与CP患者的气道结构差异及呼吸控制能力有关, 导致其呼气过程中气体排出的速度和时间较短。

在预设特征中, 吸气期z40组间差异较小但仍具有统计学意义 ($P=0.026$, 效应量 $r=0.064$), 提示CP组在呼吸过程中存在某些轻微的异常, 可能对气流控制产生影响。然而, 在tPXF/tX和vPXF/vX指标上, 两组在吸气和呼气期均无显著差异 ($P>0.05$), 这表明两组在肺功能的峰值流量和相应的相位时间上没有显著不同。

Tau在吸气期CP组显著较低 ($P=0.004$, 效应量 $r=0.081$), 可能指向CP组在气流应对上的效率较低, 表现出较低的相位时间常数。这可能与CP患者的气道形态和呼吸生理学的差异有关。总体来看, CP组在时间域上的显著差异, 特别是在

tPhase和Tau等指标上, 可能与CP患者的解剖结构和呼吸生理特点密切相关, 这些差异可能影响肺部气流模式和肺功能。

2.4 气流域异质性

气流域指标见图5。吸气期的MeanFlow、PeakFlow、Flow25/50/75及Flow25-75两组相近 (均 $P\geq 0.248$, 效应量 $r\leq 0.039$); 而在呼气期, 上述各指标在CP组均显著高于NC组 ($P<0.001$, 效应量 r 为0.193~0.236)。这表明, 尽管在吸气期两组的气流差异较小, 可能表明CP患者的基本呼吸功能较为接近正常组, 但在呼气期, CP组的气流显著增大, 提示CP组可能存在气道受限或异常的呼吸模式。CP组的高流量值可能反映了其肺部气道的补偿性机制, 试图通过增强呼气流来克服气道的部分受限, 尤其是在复杂的语音呼吸任务中。

此外, 气流波动较大的CP组可能与其上呼吸道的形态学变化和咽部肌肉控制的协调性不足有关。这可能导致呼气时气流的波动增大, 从而影响肺部的气流模式和气体交换效率。总的来说, CP组在气流域表现出的显著差异, 尤其是在呼气期的流量和波动性, 可能与CP患者的气道结构差异以及呼吸生理特点密切相关。

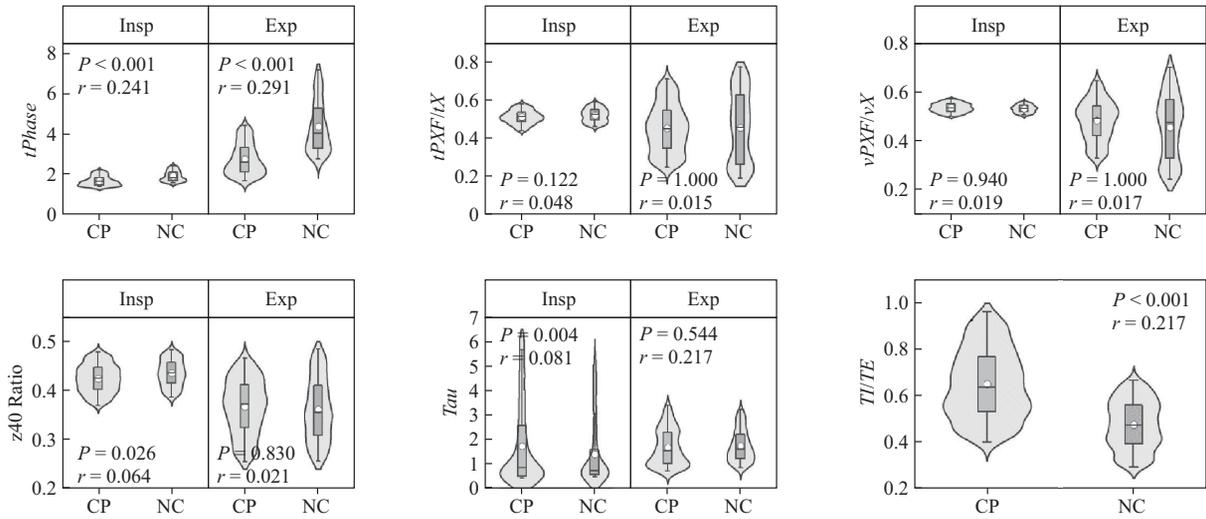


Fig. 4 Temporal heterogeneity during speech-respiratory tasks by ST-EIT

Violins show kernel density for CP and NC in inspiration and expiration across *tPhase*, *tPXF/tX*, *vPXF/vX*, *z40_Ratio*, *Tau*, and *TI/TE*. The central line marks the median, the box indicates the IQR, whiskers extend to 1.5×IQR, and violin width is proportional to data density. Abbreviations: CP, cleft palate; NC, normal control; *tPhase*, phase duration; *tPXF/tX*, time to peak flow ratio; *vPXF/vX*, volume at peak flow ratio; *Tau*, time constant; *TI/TE*, inspiratory-to-expiratory time ratio.

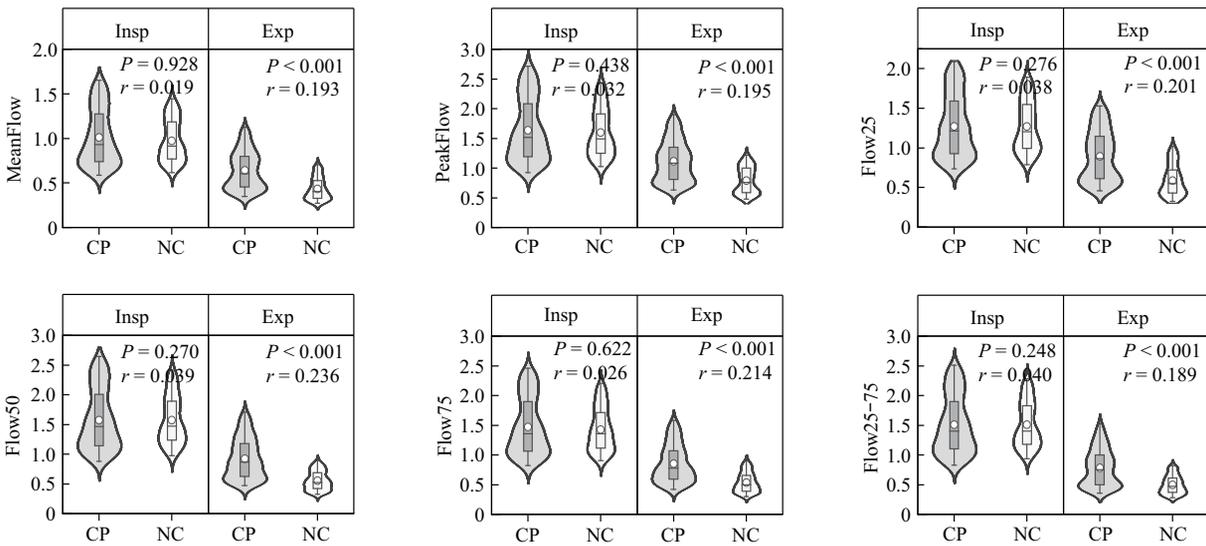


Fig. 5 Airflow heterogeneity of speech-respiratory tasks by ST-EIT

Violins show kernel density for CP and NC in inspiration and expiration across MeanFlow, PeakFlow, Flow25/50/75, and Flow25-75. The central line marks the median, the box indicates the IQR, whiskers extend to 1.5×IQR, and violin width is proportional to data density. Abbreviations: IQR, interquartile range; MeanFlow, mean flow; PeakFlow, peak flow; Flow25/50/75, instantaneous flow at 25%/50%/75% of tidal volume; Flow25-75, average flow between 25% and 75% of tidal volume.

2.5 空间域异质性

空间域指标见图6。全局潮气阻抗变化 (*TIV*) 在吸气期和呼气期的组间差异均显著 (吸气期: $P < 0.001$, 效应量 $r = 0.109$; 呼气期: $P = 0.004$, 效应量 $r = 0.079$)。CP组在吸气期的 *TIV* 显著低于NC组 (41.75 [27.03, 70.30] vs. 54.47 [31.86,

76.70]), 而在呼气期, CP组的 *TIV* 仍然低于NC组 (44.02 [26.50, 71.13] vs. 54.11 [31.14, 77.72])。这些差异可能与CP患者的局部气道结构差异和肺顺应性变化有关, CP组患者在气道的气流和气体交换上可能存在一定的限制。

在区域层面, CP组在ROI1和ROI4的 *TIV* 占

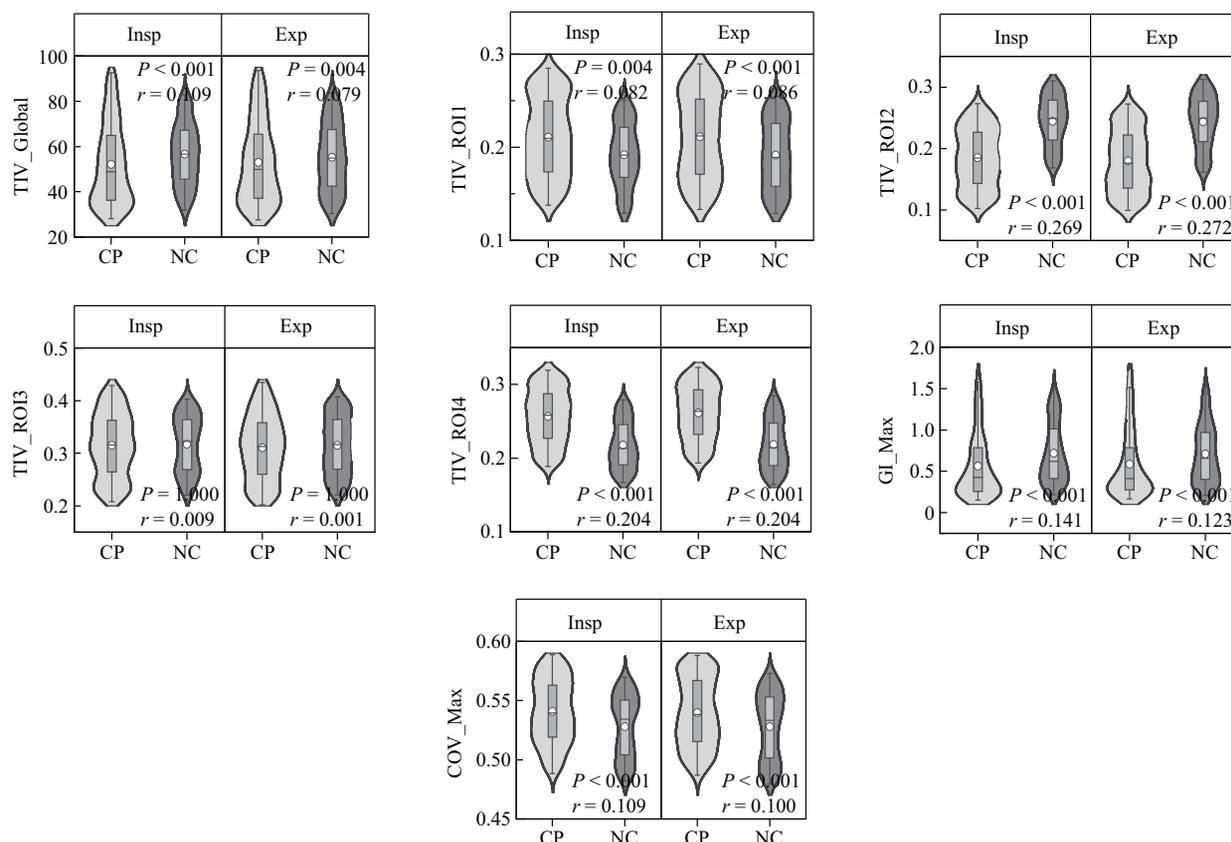


Fig. 6 Spatial heterogeneity of speech-respiratory tasks by ST-EIT

Violins show kernel density for CP and NC in inspiration and expiration across TIV, ROI1-4, GI, and CoV. The central line marks the median, the box indicates the IQR, whiskers extend to $1.5 \times \text{IQR}$, and violin width is proportional to data density. Abbreviations: TIV, tidal impedance variation; ROI, region of interest; GI, global inhomogeneity; CoV, center of ventilation.

比显著升高 ($P < 0.001$, 效应量 r 分别为 0.082 和 0.086), 而在 ROI2 则显著降低 ($P < 0.001$, 效应量 r 为 0.269 和 0.272)。这表明 CP 组在特定区域 (如 ROI1 和 ROI4) 可能存在补偿性气流增加, 或者这些区域气道的通气性较差, 导致气流分布的不均匀。ROI3 的差异不显著, 表明该区域的气道受限较少或气流分布较为正常。

全局不均匀性 (GI) 在两组间差异较小, CP 组仅在吸气末期表现出略低的 GI ($P = 0.011$, 效应量 $r = 0.141$), 这可能表明 CP 患者的气流分布在一定程度上较为均匀, 或者由于某些呼吸模式的改变导致气流的分布性变化。通气中心 (CoV) 在两相中 CP 组均略高于 NC 组 ($P \leq 0.024$, 效应量 $r \leq 0.109$), 表明 CP 组的气流分布更加分散, 尤其是在呼吸过程中, CP 患者可能由于气道的狭窄或阻力增加, 导致气流分布不均匀。这种空间域的不均匀性, 可能会影响到气体的交换效率以及整体肺功能的表现。

ST-EIT 在时间、气流与空间三域的汇总指标

见表 4。总体来说, CP 组在空间域的异质性表现出了一些与气道解剖结构和肺部通气功能相关的差异, 这些差异可能与 CP 的生理特征以及呼吸生理学的调节机制密切相关。

3 可解释性分析

3.1 机器学习模型的可解释性

本研究使用了 XGBoost 作为分类器, 并针对 5 类数据源 (鼻音计、肺量计法、Insp-EIT、Exp-EIT、ST-EIT) 进行了独立训练。为了评估模型在不同数据源上的表现, 本文采用了分层五折交叉验证方法。每折将数据分为训练集和验证集, 模型在训练集上进行拟合, 并在验证集上评估其性能。最终的预测结果以 0.5 为阈值计算混淆矩阵。本文使用包括曲线下面积 (area under the curve, AUC)、准确率 (Accuracy)、精确率 (Precision)、召回率 (Recall) 和 F1 分数 (F1-score) 在内的多个性能指标, 且所有指标均以均值 \pm 标准差汇总 (图 7)。

为了增强模型的可解释性, 采用 SHAP 方法,

Table 4 ST-EIT respiratory metrics by domain and phase with between-group comparisons (CP vs. NC)

Category	Metric	Phase	CP (n=37)	NC (n=38)	P-value	Effect (r)	
Temporal domain	tPhase	Insp	1.60 [1.40, 2.05]	1.85 [1.60, 2.35]	<0.001	0.241	
		Exp	2.45 [1.70, 4.35]	3.95 [2.80, 6.55]	<0.001	0.291	
	tPXF/tX	Insp	0.50 [0.45, 0.56]	0.51 [0.46, 0.55]	0.122	0.048	
		Exp	0.41 [0.24, 0.64]	0.42 [0.18, 0.74]	1.000	0.015	
	vPXF/vX	Insp	0.51 [0.48, 0.53]	0.51 [0.48, 0.53]	0.940	0.019	
		Exp	0.45 [0.30, 0.57]	0.46 [0.22, 0.70]	1.000	0.017	
	z40_Ratio	Insp	0.43 [0.39, 0.48]	0.44 [0.40, 0.48]	0.026	0.064	
		Exp	0.38 [0.30, 0.45]	0.36 [0.29, 0.46]	0.830	0.021	
	Tau	Insp	0.58 [0.44, 3.81]	0.64 [0.48, 3.47]	0.004	0.081	
		Exp	1.70 [0.79, 3.42]	1.74 [1.06, 3.15]	0.544	0.217	
		TI/TE	-	0.66 [0.42, 0.92]	0.49 [0.32, 0.66]	<0.001	0.217
	Airflow domain	MeanFlow	Insp	0.84 [0.56, 1.38]	0.89 [0.61, 1.34]	0.928	0.019
			Exp	0.55 [0.34, 0.88]	0.40 [0.27, 0.68]	<0.001	0.193
		PeakFlow	Insp	1.35 [0.89, 2.26]	1.46 [1.00, 2.22]	0.438	0.032
Exp			0.97 [0.61, 1.49]	0.71 [0.48, 1.13]	<0.001	0.195	
Flow25		Insp	1.07 [0.72, 1.73]	1.15 [0.78, 1.76]	0.276	0.038	
		Exp	0.75 [0.45, 1.29]	0.51 [0.32, 0.95]	<0.001	0.201	
Flow50		Insp	1.31 [0.85, 2.21]	1.42 [0.96, 2.20]	0.270	0.039	
		Exp	0.79 [0.45, 1.33]	0.51 [0.32, 0.82]	<0.001	0.236	
Flow75		Insp	1.21 [0.80, 2.07]	1.31 [0.89, 2.03]	0.622	0.026	
		Exp	0.72 [0.41, 1.24]	0.50 [0.30, 0.84]	<0.001	0.214	
Flow25-75		Insp	1.25 [0.80, 2.12]	1.35 [0.93, 2.09]	0.248	0.040	
		Exp	0.65 [0.34, 1.19]	0.45 [0.28, 0.79]	<0.001	0.189	
Spatial domain		TIV_Global	Insp	41.75 [27.03, 70.30]	54.47 [31.86, 76.70]	<0.001	0.109
			Exp	44.02 [26.50, 71.13]	54.11 [31.14, 77.72]	0.004	0.079
	TIV_ROI1	Insp	0.21 [0.14, 0.29]	0.19 [0.13, 0.26]	0.004	0.082	
		Exp	0.21 [0.14, 0.29]	0.19 [0.13, 0.26]	<0.001	0.086	
	TIV_ROI2	Insp	0.18 [0.10, 0.26]	0.25 [0.17, 0.30]	<0.001	0.269	
		Exp	0.17 [0.10, 0.25]	0.25 [0.16, 0.30]	<0.001	0.272	
	TIV_ROI3	Insp	0.32 [0.22, 0.43]	0.33 [0.23, 0.41]	1.000	0.009	
		Exp	0.32 [0.22, 0.44]	0.33 [0.23, 0.41]	1.000	0.001	
	TIV_ROI4	Insp	0.27 [0.20, 0.32]	0.21 [0.17, 0.27]	<0.001	0.204	
		Exp	0.27 [0.20, 0.33]	0.22 [0.17, 0.28]	<0.001	0.204	
	GI_Max	Insp	0.33 [0.14, 0.84]	0.55 [0.21, 1.24]	<0.001	0.141	
		Exp	0.34 [0.15, 0.90]	0.58 [0.20, 1.17]	<0.001	0.123	
	COV_Max	Insp	0.54 [0.50, 0.59]	0.54 [0.48, 0.57]	<0.001	0.109	
		Exp	0.54 [0.50, 0.59]	0.54 [0.48, 0.57]	<0.001	0.100	

Data are reported as median [IQR]. Two-sided Mann-Whitney U tests compared CP vs NC within each phase. Abbreviations: ST-EIT, spatiotemporal electrical impedance tomography; CP, cleft palate; NC, normal control; Insp, inspiration; Exp, expiration; TIV, tidal impedance variation; ROI, region of interest; GI, global inhomogeneity; CoV, center of ventilation; tPXF/tX, time to peak flow/phase time; vPXF/vX, volume at peak flow/phase tidal volume; Tau, phase time constant; IQR, interquartile range.

利用平均绝对 SHAP 值来衡量每个特征对模型决策的贡献。SHAP 方法提供了对模型中每个特征影响力的清晰理解, 识别出哪些特征对分类结果影响最

大。通过这种方式, 能够准确量化每个特征的贡献, 从而提升模型的透明度和可解释性, 为模型的结果提供更充分的生理学和临床背景解释。

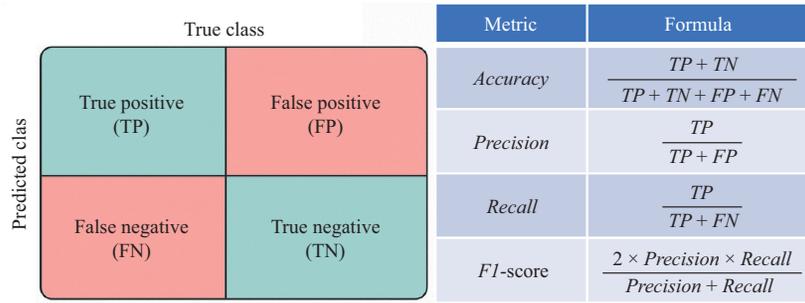


Fig. 7 Confusion matrix and evaluation metrics

Binary confusion matrix with predicted class on the y-axis and true class on the x-axis. Quadrants indicate TP, FP, FN, and TN. CP is treated as the positive class and NC as the negative class.

3.2 分类性能对比

通过逐步增加数据源，模型性能得到了显著提高。从基础的常规信号（肺量计法、鼻音计）到单相EIT（Insp-EIT、Exp-EIT），再到双相融合的ST-EIT，模型的分类能力逐步增强。特别是ST-EIT，在 $AUC=0.915\pm0.012$ ， $Accuracy=0.843\pm0.019$ ， $Precision=0.869\pm0.010$ ， $Recall=0.875\pm$

0.028 ， $F1\text{-score}=0.872\pm0.017$ 等多个指标上均表现出了最佳的性能。相比之下，肺量计法与鼻音计的判别力较为中等（ AUC 分别为 0.625 ± 0.190 和 0.721 ± 0.127 ），而单相EIT（Insp-EIT 0.875 ± 0.012 ， Exp-EIT 0.896 ± 0.016 ）已经表现出较强的区分度。表5和图8展示了不同数据源下模型的性能结果。

Table 5 Model performance by five data sources (stratified 5-fold cross-validation; mean±SD)

Metric	Lung	Nasal	Insp-EIT	Exp-EIT	ST-EIT
AUC	0.625±0.190	0.721±0.127	0.875±0.012	0.896±0.016	0.915±0.012
Accuracy	0.646±0.151	0.661±0.086	0.813±0.022	0.818±0.018	0.843±0.019
Precision	0.598±0.178	0.644±0.113	0.849±0.020	0.848±0.015	0.869±0.010
Recall	0.573±0.206	0.638±0.140	0.844±0.035	0.857±0.020	0.875±0.028
F1-score	0.576±0.174	0.631±0.101	0.846±0.020	0.852±0.015	0.872±0.017

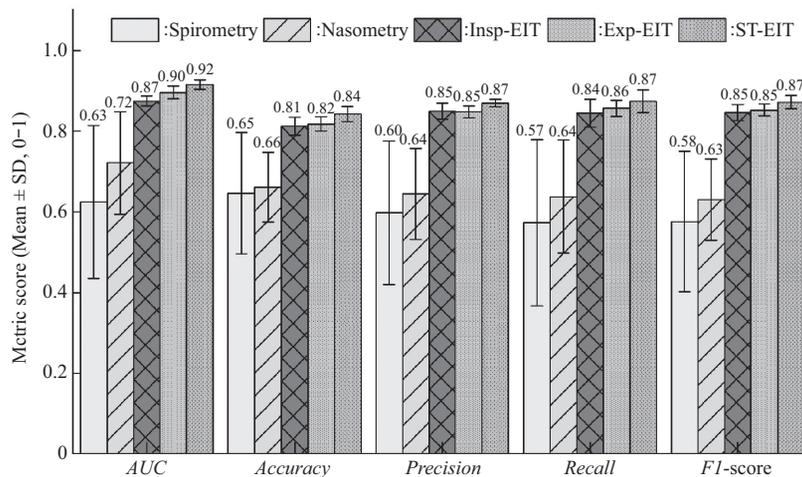


Fig. 8 Cross-source model performance across five data streams

Bars show mean scores and error bars indicate ±SD from stratified 5-fold cross-validation for five data sources: Spirometry, Nasometry, Insp-EIT, Exp-EIT, and ST-EIT. Metrics (0–1) include AUC, Accuracy, Precision, Recall, and F1-score. ST-EIT yields the highest performance across metrics.

3.3 特征贡献分析

在特征贡献分析方面, 本文采用SHAP值来评估各个特征对模型决策的影响。如图9所示, 在全局层面, 特征的贡献呈现出明显的分层结构, 空间域的贡献最高, 占53.4%, 其次是时间域(25.0%)和气流域(21.6%)。进一步细化至“吸/呼×时间/

气流/空间”6个子类, 贡献依次为: 呼气空间(27.58%)、吸气空间(25.82%)、呼气气流(16.44%)、呼气时间(14.64%)、吸气时间(10.40%)和吸气气流(5.12%)。可以看出, 呼气相关的时序与空间信息对分类的贡献最大。

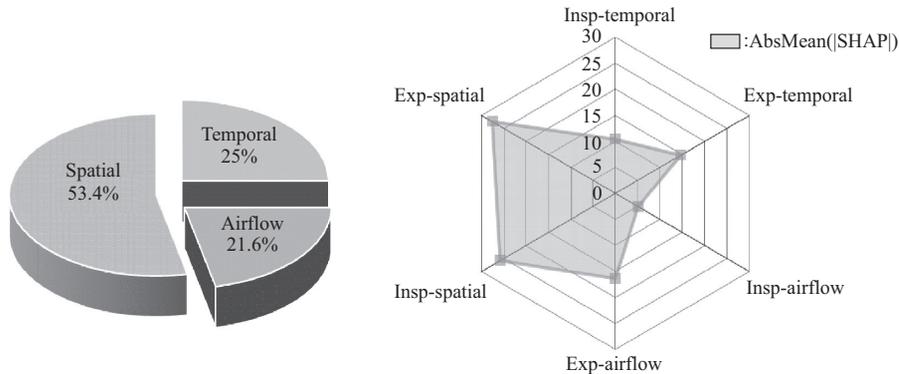


Fig. 9 Domain-level contribution to ST-EIT classifier (mean |SHAP|)

(a) Pie chart of feature-domain shares: Spatial 53.4%, Temporal 25.0%, Airflow 21.6% (averaged over 5 folds; normalized to 100%). (b) Radar plot of six subdomains (Insp/Exp×Temporal/Airflow/Spatial), highlighting dominant contributions from Exp-spatial and Insp-spatial.

如图10所示, 局部特征贡献的分析显示, 正确分类的样本通常由少数关键特征产生较大的正向SHAP值将预测推向CP, 而临界或误分类的样本则由更少的特征主导, 并且这些特征的贡献幅度较小且符号不一致。按数据源分析, 肺量计法的VC贡献最大, 鼻音计的s_NSI、s_OSI对分类的贡献最显著。对于EIT数据源, Insp-EIT中的TIV_ROI2和TIV_ROI4占主导, Exp-EIT中tPhase和TIV_ROI2、TIV_ROI4以及PeakFlow、Flow25-75对模型分类影响较大。

特别地, 在ST-EIT的双相融合模型中, 呼气期的tPhase贡献最大, 其后是吸气和呼气期的TIV_ROI2、PeakFlow、Flow25-75、TIV_Global等特征, 呈现出“时间+空间主导、气流协同”的结构。通过融合双相数据, ST-EIT模型表现出最优的分类能力。

通过SHAP值的全局和局部分析, 深入探讨了各个特征在模型中的作用, 识别了对CP与NC组区分具有显著贡献的关键特征。综上所述, 双相融合的ST-EIT通过整合呼气主导的时序和空间信息, 实现了最优的区分度, 为气流特征提供了稳定的辅助支持。

3.4 技术局限性讨论

尽管本研究验证了ST-EIT在CP言语呼吸功能评估中的临床价值, 但EIT技术本身仍存在一些局限性。

首先是空间分辨率的限制。尽管EIT具备卓越的时间分辨率, 能够灵敏捕捉肺通气的动态时序变化, 但相较于CT或MRI等传统解剖影像, 其空间分辨率较低, 对微小结构病变的成像能力有限。为弥补这一不足, 本研究并未追求解剖结构的精细还原, 而是侧重于功能性特征的提取。本文通过低通滤波等预处理手段净化呼吸信号, 确保了连续呼吸周期中时空指标(如区域TIV占比)的提取稳定性, 从而在功能层面提供了可靠的评估依据。

其次, 个体解剖差异的影响不容忽视。受试者的胸廓形态、皮下脂肪厚度及肺组织顺应性存在异质性, 这可能导致阻抗灵敏度分布的偏差。为降低由此带来的组间变异, 本文在图像重建过程中采用了统一的标准胸腔轮廓模型, 并通过标准化电极位置和时间差分成像算法来减少此类误差的影响。尽管这在一定程度上忽略了受试者的几何特异性, 但有效地保证了算法在不同个体之间的一致性, 减少了因几何适配误差引起的结果不稳定性。

未来, 计划开展多中心、大样本的研究, 进一

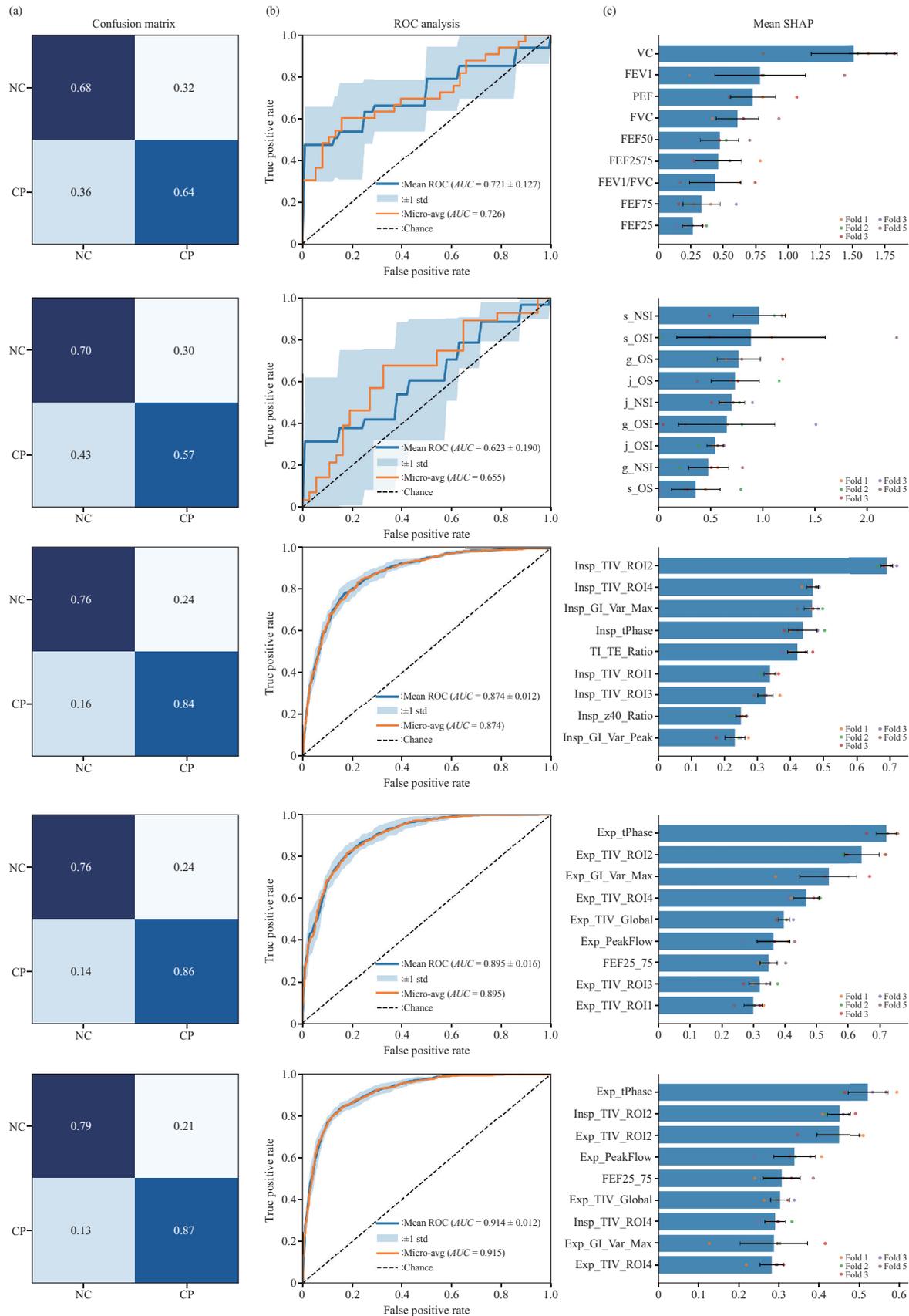


Fig. 10 XGBoost-SHAP results across different data sources

(a) Normalized confusion matrix (rows: true class; columns: predicted class; CP positive, NC negative); (b) mean ROC across 5 folds with \pm SD shading; (c) global feature ranking by mean absolute SHAP value. Rows correspond to data sources: Nasometry, Spirometry, Insp-EIT, Exp-EIT, and ST-EIT.

步引入基于个体解剖先验信息的重建算法, 从而全面提升EIT在复杂临床场景中的适用性和准确性。

4 结 论

本研究在发声情境下引入双相ST-EIT, 揭示了常规肺量计法与鼻音计难以捕捉的言语呼吸通气模式。跨源比较显示, 模型判别力由鼻音计、肺量计法依次提升至单相EIT (Insp/Exp), 并在ST-EIT达到最佳。与正常对照相比, CP个体呈现吸、呼两相 $tPhase$ 均缩短、 TI/TE 升高, 吸气期气流接近而呼气期气流普遍升高, 空间上整体 TIV 变化有限但区域分布重排 ($ROI1/ROI4 \uparrow$ 、 $ROI2 \downarrow$), GI 变化较大、 CoV 略增。这些结果构成了区分CP组与NC组的相位分辨“时间-气流-空间”综合表型。

可解释性分析进一步阐明了模型依据。SHAP指示时间与气流特征 ($tPhase$ 、 TI/TE 、分位流量等) 贡献居前, 空间指标 (TIV 、 ROI 、 GI 、 CoV) 提供一致的佐证; 个体层面表现为正确分类由少数关键特征共同驱动, 而临界/误判样本贡献幅度减弱且方向混杂。由此可见, 性能提升主要源自双相ST-EIT中与呼气相关的时序与空间信息, 而非单一幅度型指标, 提供了清晰、可生理解释的证据链。

在应用层面, ST-EIT无创、可床旁、具高时间分辨率, 适用于在近正常肺功能背景下快速表征呼吸时序与分布, 可用于CP人群的筛查、表型化与干预随访。总体而言, ST-EIT以“时间-空间主导、气流佐证”的机制实现对CP言语呼吸功能的可解释性评估, 并具有良好的临床转化可行性与研究追踪价值。

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Spatiotemporal Electrical Impedance Tomography for Speech Respiratory Assessment in Cleft Palate: an Interpretable Machine Learning Study*

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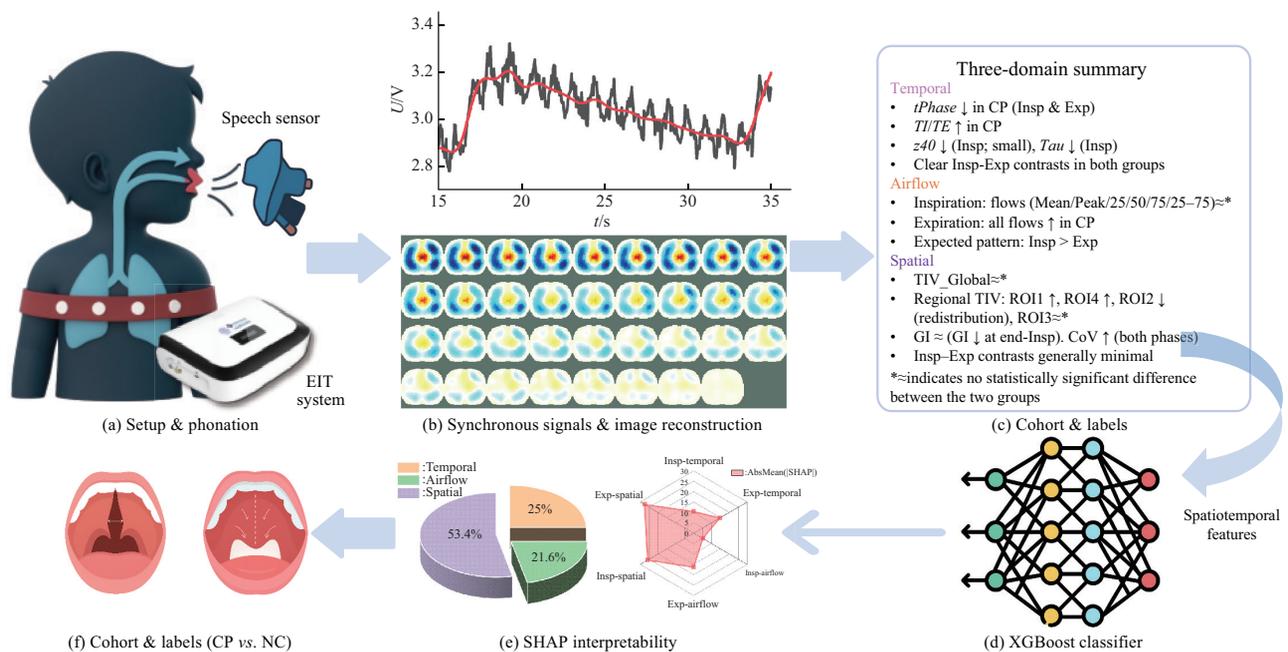
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Graphical abstract



Abstract Objective Cleft palate (CP) is a common congenital deformity often associated with velopharyngeal insufficiency (VPI), which disrupts the physiological coupling between respiration and speech. Conventional clinical assessments, such as nasometry and spirometry, provide limited static data and fail to visualize the

* This work was supported by grants from The National Natural Science Foundation of China (62501288), the China Postdoctoral Science Foundation (2025M771376, 2025M771364), the Shaanxi Provincial Science and Technology Program (2025GH-YBXM-007), and the Jiangsu Provincial Science and Technology Program Special Fund (BZ2024036).

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Received: October 27, 2025 Accepted: January 9, 2026

dynamic spatiotemporal distribution of lung ventilation during phonation. This study introduces spatiotemporal electrical impedance tomography (ST-EIT) to evaluate speech-respiratory functional features in CP patients compared to normal controls (NC). The aim is to characterize multi-domain respiratory patterns and to validate an interpretable machine learning framework for providing objective, quantitative evidence for clinical assessment.

Methods Seventy-five participants were enrolled in this study, comprising 37 patients with surgically repaired CP and 38 healthy volunteers matched for age, gender, and body mass index (BMI). All subjects performed standardized sustained phonation tasks while undergoing synchronous monitoring with a 16-electrode EIT system and a pneumotachograph. A comprehensive feature engineering pipeline was developed to extract physiological parameters across 3 complementary domains. (1) Temporal domain: including inspiratory/expiratory phase duration (tPhase), time constants (Tau), and inspiratory-to-expiratory time ratios (TI/TE); (2) airflow domain: comprising mean flow, peak flow, and instantaneous flow at 25%, 50%, and 75% of tidal volume; and (3) spatial domain: quantifying global and regional tidal impedance variation (TIV), global inhomogeneity (GI), and center of ventilation (CoV). Extreme Gradient Boosting (XGBoost) classifiers were trained using 5 distinct data sources (Spirometry, Nasometry, Inspiratory-EIT, Expiratory-EIT, and fused ST-EIT). Model performance was rigorously evaluated *via* stratified 5-fold cross-validation, and Shapley additive explanations (SHAP) were employed to quantify global and local feature contributions.

Results The CP group exhibited a distinct respiratory phenotype compared to controls. In the temporal domain, CP patients showed significantly shorter inspiratory (1.60 s vs. 1.85 s, $P < 0.001$) and expiratory phase durations (2.45 s vs. 3.95 s, $P < 0.001$), indicating a rapid, shallow breathing rhythm. In the airflow domain, while inspiratory flows were comparable, the CP group demonstrated significantly elevated mean and peak flows during the expiratory phase ($P < 0.001$), reflecting compensatory respiratory effort. Spatially, CP patients presented significant ventilation redistribution, characterized by higher regional TIV in the right-anterior (ROI1) and left-posterior (ROI4) quadrants, but lower TIV in the left-anterior (ROI2) quadrant. In terms of diagnostic accuracy, the multi-modal ST-EIT model achieved the highest performance ($AUC: 0.915 \pm 0.012$, $Accuracy: 0.843 \pm 0.019$, $F1\text{-score}: 0.872 \pm 0.017$), substantially outperforming models based on spirometry ($AUC: 0.721$) or nasometry ($AUC: 0.625$) alone. Interpretability analysis revealed that spatial domain features were the most critical, contributing 53.4% to the model's decision-making, followed by temporal (25.0%) and airflow (21.6%) features.

Conclusion ST-EIT successfully captures the temporal, airflow, and spatial deviations in CP speech respiration that are undetectable by conventional methods—specifically, rapid phase transitions, hyperdynamic expiratory airflow, and regional ventilation heterogeneity. This study validates ST-EIT as a robust, non-invasive, and radiation-free tool for characterizing speech-respiratory dysfunction, offering high clinical value for bedside screening, rehabilitation planning, and longitudinal monitoring of patients with cleft palate.

Key words electrical impedance tomography, cleft palate, speech respiratory function, spatiotemporal features, machine learning, explainable analysis

DOI: 10.3724/j.pibb.2025.0462

CSTR: 32369.14.pibb.20250462