

• 临床研究 •

膈肌和外周骨骼肌超声回声特征与脓毒症机械通气患者临床结局的关系

孙晨靓¹, 王帆^{1,2}, 余磊³, 黄俐珍^{1,2}, 赵宏胜¹, 郭凤梅⁴, 沈浩亮^{1*}

¹南通大学附属医院重症医学科, 江苏 南通 226001; ²南通大学医学院, 江苏 南通 226001; ³江西中医药大学附属洪都中医院重症医学科, 江西 南昌 330006; ⁴东南大学附属中大医院重症医学科, 江苏 南京 210009

[摘要] 目的: 探讨膈肌和外周骨骼肌超声回声特征的变化以及与脓毒症机械通气患者通气结局和预后的关系, 以探索肌肉超声在指导脓毒症患者早期精准评估中的潜在价值。方法: 选取2023年1月—2024年12月入住南通大学附属医院重症医学科(Intensive Care Unit, ICU)的脓毒症机械通气患者为研究对象, 连续观察并分析患者入ICU时、入ICU 48 h和出ICU时的膈肌和股四头肌超声图像, 计算膈肌回声强度(echogenicity of diaphragm, EDi)/股直肌回声强度(echogenicity of rectus femoris, ERF)比值(EDi/ERF)、膈肌厚度(thickness of diaphragm, Tdi)/股四头肌厚度(quadriceps muscle layer thickness, Q-MT)比值(Tdi/Q-MT)。根据患者EDi/ERF、Tdi/Q-MT变化趋势, 将患者分为比值增高组及比值降低组。分别比较两组患者的脱机成功率、机械通气时间、住院时间、28 d生存率等, 以评价膈肌与外周骨骼肌的超声特征变化对脓毒症机械通气患者临床结局的指导价值。结果: 共有110例患者纳入研究, EDi/ERF比值增高组患者的脱机成功率显著低于EDi/ERF比值降低组($P=0.043$), 机械通气时间显著长于EDi/ERF比值降低组($P=0.019$), 28 d生存率显著低于EDi/ERF比值降低组($P=0.008$); Tdi/Q-MT比值增高组与Tdi/Q-MT比值降低组在脱机成功率、机械通气时间、28 d生存率方面差异均无统计学意义($P>0.05$)。Cox比例风险模型分析结果表明, EDi增强及EDi/ERF比值增加是影响患者28 d累积脱机成功率的重要危险因素($HR=0.306, P=0.045$; $HR=0.287, P=0.031$)。结论: 脓毒症机械通气患者早期出现膈肌回声强度增高、膈肌与外周骨骼肌回声强度比值增高均与更低的脱机成功率和更差的临床预后有关。

[关键词] 脓毒症; 机械通气; 肌肉超声; 超声回声强度; 脱机; 临床结局

[中图分类号] R459.7

[文献标志码] A

[文章编号] 1007-4368(2026)02-231-10

doi: 10.7655/NYDXBNSN250493

Relationship between ultrasound echo characteristics of the diaphragm and peripheral skeletal muscles and clinical outcome in mechanically ventilated patients with sepsis

SUN Chenliang¹, WANG Fan^{1,2}, YU Lei³, HUANG Lizhen^{1,2}, ZHAO Hongsheng¹, GUO Fengmei⁴, SHEN Haoliang^{1*}

¹Department of Critical Care Medicine, Affiliated Hospital of Nantong University, Nantong 226001; ²Medical School of Nantong University, Nantong 226001; ³Department of Critical Care Medicine, Hongdu Traditional Chinese Medicine Hospital Affiliated to Jiangxi University of Chinese Medicine, Nanchang 330006; ⁴Department of Critical Care Medicine, Zhongda Hospital Southeast University, Nanjing 210009, China

[Abstract] **Objective:** To investigate the relationship between changes in ultrasound echo characteristics of the diaphragm and peripheral skeletal muscles and weaning outcome and prognosis in mechanically ventilated patients with sepsis, in order to explore the potential value of muscle ultrasound in guiding the early and accurate assessment of patients with sepsis. **Methods:** Mechanically ventilated septic patients admitted to the Department of Critical Care Medicine of Affiliated Hospital of Nantong University from January 2023 to December 2024 were selected as the study subjects, and the ultrasound images of diaphragm and quadriceps femoris were consecutively observed and analyzed at the time of admission to the ICU, 48h, and discharge from the ICU. The echogenicity of diaphragm (EDi)/echogenicity of rectus femoris (ERF) ratio (EDi/ERF) and the thickness of diaphragm (Tdi)/quadriceps muscle layer

[基金项目] 南通市卫生健康委员会科研课题基金(MS2024015)

*通信作者(Corresponding author), E-mail: shlkfc@126.com(ORCID: 00009-0006-9488-1727)

thickness (Q-MT) ratio (Tdi/Q-MT) were calculated. According to the trend of EDi/ERF and Tdi/Q-MT, the patients were categorized into the group with increasing ratio and the group with decreasing ratio. The weaning success rate, duration of mechanical ventilation, length of stay, and 28-day survival rate of the two groups were compared separately to evaluate the guiding value of changes in the ultrasound characteristics of the diaphragm and peripheral skeletal muscles on the clinical outcome of mechanically ventilated patients with sepsis. **Results:** A total of 110 patients were enrolled in the study, and the patients in the group with increased EDi/ERF ratio had a significantly lower weaning success rate ($P=0.043$), a significantly longer mechanical ventilation time ($P=0.019$), and a significantly lower 28-day survival rate ($P=0.008$) than those in the group with decreased EDi/ERF ratio. No statistically significant differences in weaning success rate, duration of mechanical ventilation, and 28-day survival rate were found between the group with increased Tdi/Q-MT ratio and decreased Tdi/Q-MT ratio ($P > 0.05$). The Cox proportional hazards model showed that enhanced EDi and increased EDi/ERF ratio were significant risk factors affecting the 28-day cumulative weaning success rate (HR=0.306, $P=0.045$; HR=0.287, $P=0.031$, respectively). **Conclusion:** The early presence of increased echogenicity of diaphragm and increased diaphragm to peripheral skeletal muscle echogenicity ratio are both associated with lower weaning success rate and poorer clinical prognosis in mechanically ventilated patients with sepsis.

[Key words] sepsis; mechanical ventilation; muscle ultrasound; echogenicity; weaning; clinical outcome

[J Nanjing Med Univ, 2026, 46(02): 231-240]

脓毒症是一种可导致全身多器官功能障碍的综合征。脓毒症导致的肌肉病变称为脓毒症肌病,可累及四肢肌、膈肌及其他呼吸肌,引起肌力下降、肌肉萎缩,增加脓毒症患者的远期病死率^[1]。也有研究发现脓症患者发生膈肌萎缩的速度明显快于其他骨骼肌^[2]。作为人体最重要的呼吸肌,膈肌功能障碍近年备受关注,因为其在重症医学科(intensive care unit, ICU)机械通气患者中的发生率高,且在机械通气早期即可出现,严重影响患者的脱机结局和预后^[3-5]。此外,早年已有学者证实当脓毒症和机械通气并存时,二者还可发挥协同作用加速膈肌功能障碍发生的进程^[6-7]。因此,关注并监测脓毒症机械通气患者的膈肌和全身骨骼肌形态及功能变化对优化患者的病情评估至关重要。

随着超声技术的发展和普及,床旁超声已越来越多地被ICU医生关注并应用。近年的肌肉超声相关研究发现:超声回声强度可作为反映肌肉组织病变的潜在标志物,且超声回声强度可能是比肌肉厚度更能反映肌肉特性变化的敏感标志^[8-9]。而已有的少量相关研究发现:膈肌和外周骨骼肌回声强度增高与机械通气时间延长和不良预后有关^[10-11]。因此,肌肉回声强度增加可能提示着某种肌肉病变,其对临床结局的潜在评估价值值得深入探索。

目前有关肌肉回声强度变化特征与脓毒症机械通气患者临床结局关系的研究尚未有太多的报道。本研究假设:脓毒症机械通气患者的膈肌与外周骨骼肌超声回声变化特征和患者的脱机结局及预后有关。借助超声对膈肌及外周骨骼肌进行动

态的可视化分析,可能为脓症患者病情的早期精准评估提供更多额外的信息,并指导临床医师及时进行保护性干预。

1 对象和方法

1.1 对象

本研究为前瞻性观察性研究,纳入2023年11月—2024年12月在南通大学附属医院重症医学科接受机械通气的脓症患者。纳入标准:①年龄 ≥ 18 岁;②符合Sepsis 3.0标准诊断;③接受有创机械通气 ≥ 48 h。排除标准:①神经肌肉疾病;②严重慢性气道疾病;③影响呼吸肌评估的胸腹部疾病(如胸腹部畸形、严重胸外伤、腹腔高压);④重度肥胖(BMI > 35 kg/m²);⑤近半年内接受过机械通气治疗;⑥晚期恶性肿瘤;⑦孕产妇;⑧病情预计在24 h内死亡患者;⑨拒绝参加本研究。研究得到了医院伦理委员会的批准(伦理批准号:2023-L141),患者或其法定代理人签订书面知情同意。

1.2 方法

1.2.1 膈肌超声测量

本研究的肌肉超声测量统一选用飞利浦CX50超声仪(Philips Healthcare,美国),超声测量增益均选择机器的预设参数:增益50,深度3.5 cm,动态范围50 dB,热指数0.1,机械指数0.9。参考先前研究关于膈肌超声的测量方法^[12]:患者取半卧位,B模式下将高频线阵探头置于患者右腋前-腋中线第8~10肋间隙区域对膈肌进行扫查,标准膈肌图像为胸膜-膈肌-腹膜三层结构,膈肌厚度(thickness of dia-

phragm, Tdi)的定义为:呼气末胸膜与腹膜内缘之间的最大距离。将上述采集的膈肌超声图像以JPEG格式保存,使用Image J图像分析软件对超声回声强度进行量化。具体为:通过“跟踪法”圈取不含膈肌肌膜及伪影的最大区域为感兴趣区域(region of interest, ROI),再用软件的灰度直方图功能分析ROI的平均回声强度值,即膈肌回声强度(echogenicity of diaphragm, EDi)^[10,13](图1)。

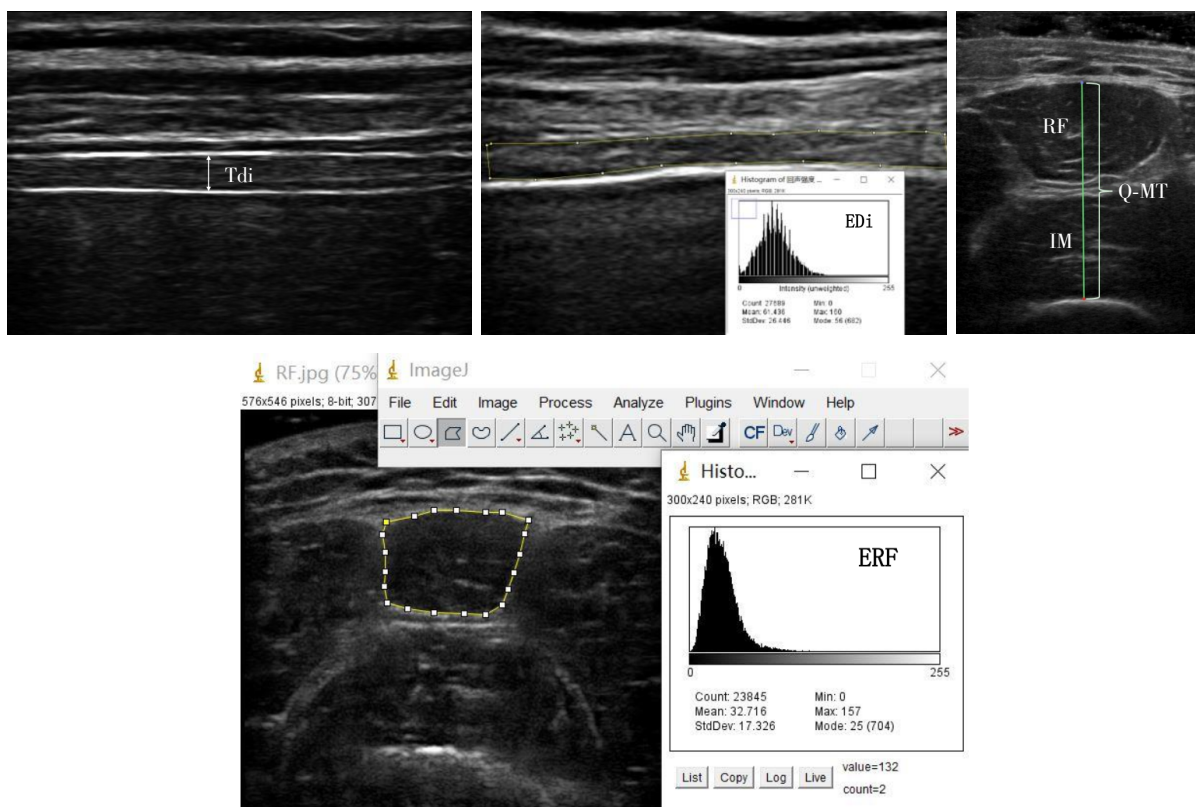
1.2.2 股四头肌超声测量

参考先前研究关于股四头肌超声测量的方法^[14]:患者取仰卧位,双膝伸直且放松,B模式下将低频曲线探头置于患者股骨前区对股四头肌进行扫查,运

用最小压缩操作手法获得清晰的股四头肌图像,测量股四头肌厚度(quadriceps muscle layer thickness, Q-MT),Q-MT定义为:股直肌浅筋膜到股骨膜的最短距离,即股直肌(rectus femoris, RF)与股中间肌(intermedius, IM)的总厚度。所采集的股四头肌超声图像同样运用Image J软件测量股直肌回声强度(echogenicity of rectus femoris, ERF),ERF定义为:通过“跟踪法”圈取不含肌膜及伪影的最大区域为ROI的平均回声强度值^[15](图1)。

1.2.3 研究定义与分组

本研究患者的呼吸机脱机拔管均由临床医师根据机械通气脱机前筛查及自主呼吸试验流程标



Tdi: thickness of diaphragm; EDi: echogenicity of diaphragm; RF: rectus femoris; IM: intermedius; Q-MT: quadriceps muscle layer thickness; ERF: echogenicity of rectus femoris.

图1 肌肉超声测量方法学

Figure 1 Methodology of muscle ultrasound measurement

准^[16]综合评估后实施,本研究的超声测量数据不用于指导临床医生的脱机决策。脱机成功的定义为拔管后48 h内不再需要接受机械通气;脱机失败定义为自主呼吸试验失败或拔管后48 h内需重新接受机械通气^[17]。肌肉萎缩定义为超声下膈肌或股四头肌厚度较基线(即入ICU时的首次测值)下降 $\geq 10\%$ ^[12,18]。肌肉回声增强定义为肌肉超声平均回声强

度较基线上升^[10]。根据纳入患者入ICU 48 h的膈肌/股直肌回声强度比值(EDi/ERF)、膈肌/股四头肌厚度比值(Tdi/Q-MT)较基线比值的变化趋势,分别将纳入患者分为比值增高组及比值降低组。

1.2.4 观察指标

主要观察指标:脱机成功率。次要观察指标:机械通气时间、ICU住院时间、总住院时间、28 d生

存率。同时观察并比较两组患者的人口统计学、病情参数等一般资料以及肌肉回声强度、肌肉厚度等超声动态监测数据。超声监测时间点为入ICU时、入ICU 48 h和出ICU时。

1.2.5 样本量估算

使用PASS21.0软件对本研究进行样本量估算：根据早期预实验的结果，EDi/ERF 比值增高与不增高的患者比例为 17/11=1.55，检验水准 α 选择 0.05，把握度(1- β)选择 0.80，选择双侧检验，计算得出研究总共所需样本量为 79 例。考虑失访、资料不合格等因素可能造成的样本量消耗，在估算样本量基础上再增加 20%；最后总需纳入至少 95 例病例以保证样本量的充足。

1.3 统计学方法

使用 SPSS26.0、GraphPad Prism8.0 统计软件进行统计分析与绘图。计量资料采用 Kolmogorov-Smirnov 检验进行正态性分析，正态分布的数据以均数 \pm 标准差($\bar{x} \pm s$)表示，组间比较采用 *t* 检验，非正态分布数据以中位数(四分位数)[$M(P_{25}, P_{75})$]表示，组间比较采用 Mann-Whitney *U* 检验；计数资料用[*n*

(%)]表示，组间比较采用 χ^2 检验或 Fisher 确切概率法。根据患者 28 d 累积脱机成功率和累积生存率，采用 Cox 比例风险回归模型分别分析可影响患者脱机结局和生存结局的肌肉超声特征相关风险因素。采用多因素 Logistic 回归模型分析与膈肌/外周骨骼肌回声强度比值增高独立相关的临床影响因素。 $P < 0.05$ 为差异有统计学意义。

2 结果

2.1 不同组间一般资料对比

研究共纳入了 110 例患者，根据肌肉回声强度比值变化趋势分组，其中 EDi/ERF 比值增高组 56 例(50.9%)，EDi/ERF 比值降低组 54 例(49.1%)。分析对比两组患者的人口统计学、初始治疗参数等基线资料，两组患者在一般资料方面的差异均无统计学意义(P 均 > 0.05)。EDi/ERF 比值增高组患者的脱机成功率显著低于 EDi/ERF 比值降低组($P=0.043$)，机械通气时间显著长于 EDi/ERF 比值降低组($P=0.019$)，28 d 生存率显著低于 EDi/ERF 比值降低组($P=0.008$, 表 1)。

表 1 两组患者一般资料及超声特征数据对比(按 EDi/ERF 比值分组)

Table 1 Comparison of baseline characteristics and ultrasound features between the two groups(grouped by EDi/ERF ratio)

Variable	Ratio increased group(n=56)	Ratio decreased group(n=54)	$\chi^2/U/Z$	<i>P</i>
Age[years, $M(P_{25}, P_{75})$]	78(68, 82)	76(69, 83)	-0.272	0.785
Sex[<i>n</i> (%)]			0.059	0.808
Male	34(60.7)	34(63.0)		
Female	22(39.3)	20(37.0)		
BMI(kg/m ² , $\bar{x} \pm s$)	23.8 \pm 3.2	24.4 \pm 3.1	-0.988	0.325
APACHE II ($\bar{x} \pm s$)	19.3 \pm 7.4	18.5 \pm 7.8	0.539	0.591
SOFA($\bar{x} \pm s$)	9.1 \pm 3.7	8.4 \pm 4.0	0.980	0.329
Septic shock[<i>n</i> (%)]			0.209	0.648
Yes	35(62.5)	36(66.7)		
No	21(37.5)	18(33.3)		
Baseline EDi[$M(P_{25}, P_{75})$]	71.3(62.4, 79.0)	76.2(69.3, 83.7)	1.794	0.073
Baseline ERF[$M(P_{25}, P_{75})$]	55.7(46.6, 69.4)	58.2(52.8, 68.0)	1.052	0.293
WBC[$\times 10^9/L$, $M(P_{25}, P_{75})$]	10.4(5.8, 16.6)	9.9(6.8, 17.2)	0.263	0.792
PCT[ng/mL, $M(P_{25}, P_{75})$]	1.07(0.19, 3.88)	2.00(0.32, 6.48)	1.195	0.232
Alb[g/L, $M(P_{25}, P_{75})$]	25.2(21.5, 28.0)	24.4(20.1, 29.1)	-0.374	0.709
Duration of MV[h, $M(P_{25}, P_{75})$]	120.0(72.0, 212.3)	66.0(17.8, 150.0)	-2.342	0.019
ICU length of stay[d, $M(P_{25}, P_{75})$]	9.5(6.0, 14.8)	7.5(4.8, 20.0)	-0.626	0.531
Total length of stay[d, $M(P_{25}, P_{75})$]	18.0(14.0, 25.8)	18.5(12.0, 28.0)	-0.371	0.711
Success rate of weaning[<i>n</i> (%)]	36(62.3)	44(81.5)	4.098	0.043
Survival rate of 28-day[<i>n</i> (%)]	38(67.8)	48(83.3)	7.129	0.008

BMI: body mass index; APACHE II: acute physiology and chronic health evaluation II; SOFA: sequential organ failure assessment; EDi: echogenicity of diaphragm; ERF: echogenicity of rectus femoris; WBC: white blood cell count; PCT: procalcitonin; Alb: albumin level; MV: mechanical ventilation; ICU: intensive care unit.

根据肌肉厚度比值变化趋势分组,其中Tdi/Q-MT比值增高组40例(36.4%),Tdi/Q-MT比值降低组70例(63.6%)。两组患者一般资料方面,除白蛋白水平外,差异均无统计学意义($P > 0.05$);Tdi/Q-MT比值增高组与Tdi/Q-MT比值降低组间在脱机成功率、机械通气时间、28 d生存率等预后指标方面差异均无统计学意义($P > 0.05$,表2)。

2.2 不同脱机结局患者的肌肉超声特征变化趋势

比较脱机成功和脱机失败患者的肌肉超声回声特征的动态变化趋势:脱机成功患者的EDi随病程呈逐渐下降趋势,在入ICU 48 h和出ICU时的EDi较前一时间点的差异具有统计学意义($P < 0.05$),而

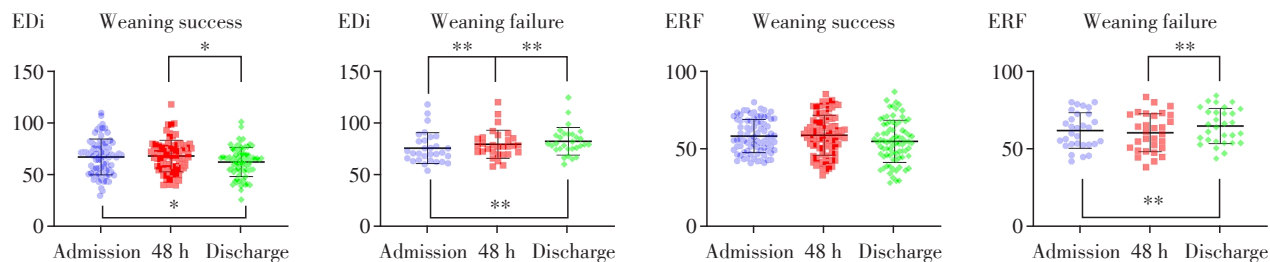
脱机失败患者的EDi随病程呈逐渐上升趋势,在入ICU 48 h和出ICU时的EDi较前一时间点的差异具有统计学意义($P < 0.01$);脱机成功患者的ERF随病程未见明显变化,而脱机失败患者的ERF在出ICU时较基线表现为明显增高($P < 0.01$,图2)。

比较脱机成功和脱机失败患者的肌肉超声厚度特征的动态变化趋势:脱机成功患者的Tdi和Q-MT随病程均未提示发生明显改变(P 均 > 0.05);脱机失败患者的Tdi随病程呈逐渐下降趋势,在入ICU 48 h和出ICU时的Tdi较前一时间点的差异具有统计学意义(P 均 < 0.01),而脱机失败患者的Q-MT随病程未见明显变化(P 均 > 0.05 ,图3)。

表2 两组患者一般资料及超声特征数据对比(按Tdi/Q-MT比值分组)

Table 2 Comparison of baseline characteristics and ultrasound features between the two groups(grouped by Tdi/Q-MT ratio)

Variable	Ratio increased group(n=40)	Ratio decreased group(n=70)	$\chi^2/t/Z$	P
Age[years, $M(P_{25}, P_{75})$]	76.0(70.3, 83.0)	77.0(68.0, 82.3)	0.060	0.995
Sex[n(%)]			0.270	0.604
Male	26(65.0)	42(60.0)		
Female	14(35.0)	28(40.0)		
BMI(kg/m ² , $\bar{x} \pm s$)	24.3 \pm 3.3	24.0 \pm 3.1	0.500	0.618
APACHE II ($\bar{x} \pm s$)	20.0 \pm 9.1	18.3 \pm 6.6	1.136	0.259
SOFA($\bar{x} \pm s$)	9.4 \pm 4.3	8.4 \pm 3.5	1.195	0.235
Septic shock[n(%)]			0.568	0.451
Yes	24(60.0)	47(67.1)		
No	16(40.0)	23(32.9)		
Baseline Tdi(cm, $\bar{x} \pm s$)	0.23 \pm 0.05	0.25 \pm 0.06	-1.302	0.196
Baseline Q-MT(cm, $\bar{x} \pm s$)	2.52 \pm 0.53	2.38 \pm 0.50	1.315	0.191
WBC[$\times 10^9/L$, $M(P_{25}, P_{75})$]	9.7(7.0, 17.4)	10.4(5.8, 15.5)	-0.326	0.744
PCT[ng/mL, $M(P_{25}, P_{75})$]	1.08(0.24, 4.58)	1.70(0.25, 5.40)	0.566	0.571
Alb[g/L, $M(P_{25}, P_{75})$]	26.2(22.5, 30.4)	24.1(20.1, 27.7)	-2.212	0.027
Duration of MV[h, $M(P_{25}, P_{75})$]	96.0(30.0, 214.5)	95.5(25.8, 168.0)	-0.401	0.688
ICU length of stay[d, $M(P_{25}, P_{75})$]	9.0(5.0, 15.0)	9.5(5.0, 14.0)	0.016	0.988
Total length of stay[d, $M(P_{25}, P_{75})$]	20.0(11.3, 28.8)	18.0(13.0, 25.8)	-0.016	0.988
Success rate of weaning[n(%)]	31(77.5)	49(70.0)	0.722	0.396
Survival rate of 28-day[n(%)]	29(72.5)	57(81.4)	1.190	0.275



EDi: echogenicity of diaphragm; ERF: echogenicity of rectus femoris; * $P < 0.05$; ** $P < 0.01$.

图2 两组患者膈肌与股四头肌回声强度变化趋势对比

Figure 2 Comparison of diaphragm and quadriceps echogenicity trends between the two groups

2.3 肌肉超声特征与临床结局的关系

为观察肌肉超声特征与脓毒症机械通气患者脱机结局的关系,通过Cox回归分析评估肌肉超声特征的相对危险程度。其中,膈肌回声增强及膈肌/外周骨骼肌回声强度比值增加是影响患者28 d累积脱机成功率的重要危险因素(HR=0.306, P=0.045; HR=0.287, P=0.031,表3)。

同样,为观察肌肉超声特征与脓毒症机械通气患者生存结局的关系,Cox回归分析显示:膈肌回声增强及膈肌/外周骨骼肌回声强度比值增加是影响患者28 d累积生存率的重要危险因素(HR=0.369, P=0.004; HR=0.386, P=0.006,表4)。

2.4 肌肉回声比值的临床影响因素

为观察膈肌/外周骨骼肌回声强度比值的影响

因素,多因素Logistic回归分析常见的相关临床因素后显示:入院48 h内的平均RASS、平均RR及平均VT与膈肌/外周骨骼肌回声强度比值增高有关(OR值>1);而年龄、BMI、性别、SOFA、APACHE II、平均CPOT未提示是膈肌/外周骨骼肌回声强度比值增高的显著影响因素(图4)。

3 讨论

脓毒症患者的肌肉病变是一项与患者预后相关并值得更多关注的临床问题。超声技术的深入应用为全面评估肌肉的形态功能提供了更多元化的手段,其价值值得深入发掘。本研究通过探索膈肌与外周骨骼肌超声特征的交互变化与临床结局的关系发现:①对于接受机械通气的脓毒症患者,

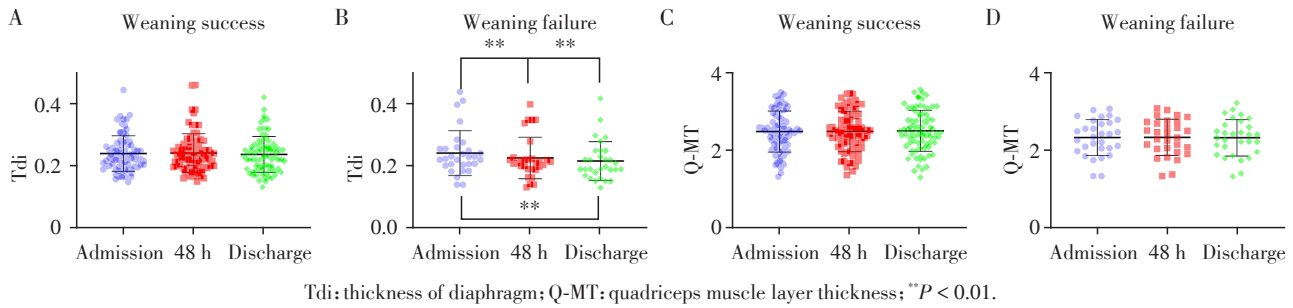


图3 两组患者膈肌与股四头肌厚度变化趋势对比

Figure 3 Comparison of diaphragm and quadriceps thickness trends between the two groups

表3 肌肉超声特征与脱机结局的关系

Table 3 Relationship between muscle ultrasound features and weaning outcome

Variable	B	SE	Wald	df	P	Exp(B)	95.0%CI for Exp(B)
EDi increased	-1.183	0.589	4.037	1	0.045	0.306	0.097-0.971
ERF increased	0.213	0.289	0.545	1	0.460	1.238	0.703-2.180
Diaphragm atrophy	-0.551	0.438	1.579	1	0.209	0.577	0.244-1.361
Quadriceps muscle atrophy	-0.036	0.287	0.016	1	0.900	0.964	0.549-1.693
EDi/ERF ratio increased	-1.250	0.581	4.632	1	0.031	0.287	0.092-0.894
Tdi/Q-MT ratio increased	0.071	0.530	0.018	1	0.893	1.074	0.380-3.035

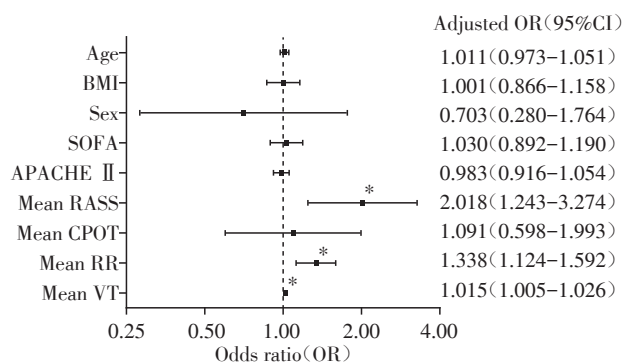
EDi: echogenicity of diaphragm; ERF: echogenicity of rectus femoris; Tdi: thickness of diaphragm; Q-MT: quadriceps muscle layer thickness.

表4 肌肉超声特征与生存结局的关系

Table 4 Relationship between muscle ultrasound features and survival outcome

Variable	B	SE	Wald	df	P	Exp(B)	95.0%CI for Exp(B)
EDi increased	-0.996	0.344	8.375	1	0.004	0.369	0.188-0.725
ERF increased	-0.184	0.287	0.408	1	0.523	0.832	0.474-1.462
Diaphragm atrophy	-0.684	0.384	3.177	1	0.075	0.505	0.238-1.071
Quadriceps muscle atrophy	0.121	0.259	0.219	1	0.640	1.129	0.679-1.876
EDi/ERF ratio increased	-0.952	0.345	7.618	1	0.006	0.386	0.196-0.759
Tdi/Q-MT ratio increased	-0.353	0.402	0.771	1	0.380	0.702	0.319-1.545

EDi: echogenicity of diaphragm; ERF: echogenicity of rectus femoris; Tdi: thickness of diaphragm; Q-MT: quadriceps muscle layer thickness.



BMI: body mass index; SOFA: sequential organ failure assessment; APACHE II: acute physiology and chronic health evaluation II; RASS: richmond agitation-sedation scale; CPOT: critical-care pain observation tool; RR: respiratory rate; VT: tidal volume; OR: odds ratio; CI: confidence interval; * $P < 0.05$.

图4 多因素 Logistic 回归: 与膈肌/外周骨骼肌回声强度比值增高的独立相关临床因素

Figure 4 Multivariate logistic regression: clinical factors independently associated with increased echogenicity ratio of diaphragm/peripheral skeletal muscle

随着通气时间延长,膈肌/股直肌回声比值增高与患者更低的脱机成功率有关;膈肌回声强度增加及膈肌/股直肌回声比值增加是影响该人群患者成功脱机和预后的重要危险因素;②相对于肌肉厚度,肌肉回声特征对患者临床结局评估具有更高的指导价值。

脓毒症是宿主应对感染出现的失控的全身炎症反应,可导致危及生命的多器官功能障碍。脓毒症除能影响循环呼吸等重要系统外,也与肌肉病变密切相关^[19-20]。研究表明脓毒症可引起肌纤维破坏、肌束萎缩、肌肉功能显著下降^[21-22]。从肌肉损伤的易感性而言,有研究发现脓毒症患者的膈肌萎缩速度和程度都明显高于其他骨骼肌^[2]。另外,呼吸衰竭作为脓毒症的最常见并发症之一,多数入住ICU的脓症患者都需接受机械通气治疗。机械通气是引起膈肌及四肢肌无力的危险因素,但膈肌无力的发生率是四肢肌无力的2倍,并对脱机结局产生直接负面影响^[23]。也有报道认为当机械通气和脓毒症并存的情况下,二者可产生协同效应加速膈肌功能障碍的发生进程^[7]。因此,充分关注并评估脓毒症机械通气患者的肌肉功能,并在机械通气过程中探寻更多关于膈肌与外周骨骼肌的特征变化信息,对于优化该人群的脱机结局和预后是至关重要的。

关于膈肌及骨骼肌的评估,传统的方法包括双

能X线吸收法、生物电阻抗分析、活检、神经肌电图或影像评估等^[24]。然而,这些技术对软硬件的专业依赖性较强,且操作复杂,多数存在电离辐射或有创,并不适用于ICU床旁^[24]。超声技术恰恰弥补了这些技术的很多不足,在近年的肌肉评估研究中其准确性也得到了验证^[25-26]。超声除了可观察肌肉的厚度特征外,还可观察其超声回声性。健康肌肉组织通常显示为“黑色”,当肌肉发生萎缩损伤等病理改变时,更多脂肪或纤维组织等会代替正常肌细胞,肌肉在超声下会表现为回声强度增加(更亮)^[27]。现有研究认为肌肉超声回声强度增高与肌肉萎缩、炎症、损伤、疲劳等多种情形都有关,具有较高的敏感性和可靠性,可作为诊断肌病或反映预后的评价指标^[8, 28];在患儿的研究中也证实了肌肉超声回声性是比肌肉厚度更能反映肌肉特性变化的敏感标志物^[9]。当前的同类研究初步发现:ICU机械通气患者发生膈肌回声强度增高的现象并不少见,且膈肌回声强度增高与更长的机械通气时间有关^[29],而近年在COVID-19患者人群中同样发现膈肌或骨骼肌回声强度均较肌肉厚度能更好地评价预后^[11]。

关于膈肌回声强度的指导价值,先前 Coiffard 等^[10]的研究已证实:不论膈肌厚度增减均能表现为回声强度的增加,且膈肌回声强度增加与机械通气延长有关。换言之,膈肌回声强度变化与机械通气时间的关系独立于膈肌厚度的改变而存在,具有更敏感反映患者临床预后的特征优势。因此,作为一种可反映ICU患者呼吸肌损伤的潜在临床标志物,膈肌回声强度值得进一步研究。然而,回声强度的变化也会受到如超声增益、探头角度、皮下组织厚度、组织水肿程度等诸多因素的干扰^[30],膈肌回声强度单一指标对临床指导价值的鲁棒性尚值得进一步的验证和优化。因此,本研究在现有系列研究的基础上,充分利用肌肉回声改变反映肌肉受损的高敏感性,创新性地分析了膈肌与外周骨骼肌超声回声交互变化特征与脓毒症机械通气患者机械通气结局和预后的关系。研究发现了EDi/ERF的早期增高与更低的脱机成功率和更高的病死率有关。此外,通过动态观察肌肉超声回声的特征趋势,发现随着机械通气时间延长,脱机成功组患者的膈肌回声强度在不断降低,而脱机失败组患者的膈肌回声强度在不断增高,但脱机成败患者的这一变化趋势特点并不能敏感地反映于膈肌厚度。

本研究中,Tdi/Q-MT同样未能显示与脱机及临床结局间存在显著关联,其潜在原因与肌肉厚度的

变化幅度以及变化的滞后性有关。因为膈肌厚度普遍很薄(通常仅2~3 mm),即使发生了膈肌萎缩,基于目前的超声技术来发现肌肉厚度的微小变化其准确性是存在挑战的^[31]。与此同时,肌肉厚度的变化往往是在肌肉组织学发生显著改变后才能显现出来,早期的肌肉损伤并不一定能很快地反映为肌肉厚度的显著改变。这一点和先前一项针对儿童骨骼肌超声的同类研究^[9]结果相类似:在肌肉回声性出现显著变化的情况下,肌肉厚度未发生明显改变。这也提示了肌肉回声性可能是比肌肉厚度更能敏感发现肌肉特性变化或提示肌肉功能障碍的早期标志物。相比膈肌超声特征,本研究中股四头肌的超声回声及厚度特征变化均相对稳定,并未能像膈肌超声特征那样较好地评估脱机结局,这与四肢肌肉和呼吸功能之间的固有关联有限有关。因此,将股四头肌为代表的患者自身骨骼肌作为“内部参照”,有助于弱化肌肉回声强度诸多干扰因素的影响,有效提升膈肌回声增加对临床指导的价值。结合本研究结果推测,在机械通气早期,当膈肌较外周骨骼肌出现了更显著的回声强度增幅可能提示已经发生了膈肌损伤。因此,膈肌与外周骨骼肌之间的这种超声回声强度的相对变化为早期发现膈肌功能障碍提供了更敏感的预警信息,有利于临床医生及时对患者进行早期的膈肌保护性干预,比如更合理的呼吸机支持强度和适度的镇痛镇静目标等^[32],从而改善患者的通气结局及总体预后。本研究中的多因素回归分析结果也与这一点相契合,即入院早期更高的躁动镇静评分(提示镇静不足)、呼吸频率和自主潮气量(提示通气支持相对不足)均与EDi/ERF比值增高有关。当然,肌肉之间回声强度的相对改变,从组织学角度是否提示明显的病理改变以及炎症因子是否在其中介导了膈肌与外周肌肉的差异损伤等,这也是后续研究值得进一步探索的。

本研究也存在一些局限性:①脓毒症患者的原发病来源异质性较大,即便研究设计阶段从纳排标准已控制了混杂因素,但患者因素对结局指标的影响在某种程度上依然存在;②尽管肌肉回声强度测量在先前研究^[33]中展示出了良好的测量可靠性,但不同超声仪间的图像差异,增益设置参数等问题对回声测量的影响仍需要考虑,未来的同类研究必须要明确和标化;③本研究尚为短期的小型观察性研究,未对患者出院后的生存、功能恢复情况等长期预后进行随访,这可能会影响结论的远期适用性;

④本研究未评估跨膈压、最大吸气压等反映膈肌功能的力学指标,现有结论无法直接关联超声特征与肌肉收缩能力;⑤基于现有研究目前尚无明确的定义超声回声增高或降低的具体界值,本研究依赖趋势的分组策略不可避免会产生一定的主观分组偏倚,未来更多的超声回声研究来共同推进相关共识的形成是值得期待的。

综上所述,脓毒症机械通气患者早期出现膈肌回声强度增高EDi/ERF增高均与患者更差的临床结局有关;通过动态评价膈肌与外周骨骼肌的超声回声强度比值变化,可较肌肉厚度更敏感地评价脓毒症患者的机械通气结局和预后,对优化该类患者的脱机评估和预测提供了更全面的信息支持,也为临床决策调整提供了一定的指导价值。

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:

孙晨靛负责研究方案的设计、数据结果的解读与文稿撰写。王帆参与研究数据的汇总及统计分析,参与部分文稿撰写。余磊负责图片数据的整理及软件分析。黄俐珍负责临床数据的收集与统计。赵宏胜负责指导研究的实施及质控。郭凤梅参与课题设计和研究指导。沈浩亮负责研究资金获取、论文审阅和修订。

Author's Contributions:

SUN Chenliang was responsible for designing of the research, interpreting data and drafting the manuscript. WANG Fan participated in data collection and statistical analysis, and contributed to portions of the manuscript. YU Lei organized image data and performed software analysis. Huang Lizhen collected and statistically analyzed clinical data. ZHAO Hongsheng guided the study implementation and ensured quality control. GUO Fengmei participated in the project design and research guidance. SHEN Haoliang was responsible for funding acquisition, reviewing and revising the manuscript.

[参考文献]

- [1] XUE Q K, ZHANG D Y, ZOU J R, et al. Treatment advances of sepsis-induced myopathy (Review)[J]. Biomed Rep, 2024, 22(2): 19
- [2] JUNG B, NOUGARET S, CONSEIL M, et al. Sepsis is associated with a preferential diaphragmatic atrophy: a critically ill patient study using tridimensional computed tomography[J]. Anesthesiology, 2014, 120(5): 1182-1191
- [3] WU H M, CHASTEEN B. Rapid review of ventilator-induced diaphragm dysfunction[J]. Respir Med, 2024, 223: 107541

- [4] POWERS S K. Diaphragm function in health and disease [J]. *Adv Exp Med Biol*, 2025, 1478: 615-630
- [5] 张倩,周静,朱冬梅,等.镇痛镇静对延长机械通气患者膈肌萎缩的影响[J].*南京医科大学学报(自然科学版)*, 2021, 41(2): 244-247
ZHANG Q, ZHOU J, ZHU D M, et al. Effects of analgesia and sedation on diaphragm atrophy in patients undergoing prolonged mechanical ventilation [J]. *Journal of Nanjing Medical University (Natural Sciences)*, 2021, 41(2): 244-247
- [6] DRES M, GOLIGHER E C, HEUNKS L M A, et al. Critical illness-associated diaphragm weakness [J]. *Intensive Care Med*, 2017, 43(10): 1441-1452
- [7] PETROF B J. Diaphragmatic dysfunction in the intensive care unit: caught in the cross-fire between sepsis and mechanical ventilation [J]. *Crit Care*, 2013, 17(4): R181
- [8] SPILIOPOULOS K C, VELTSISTA D, CHRONI E. Quantitative muscle echogenicity assessment by ultrasound and automated thresholding in myopathic and neurogenic diseases [J]. *Clin Neurophysiol*, 2023, 146: 87-88
- [9] JAIN A, SANKAR J, KABRA S K, et al. Evaluation of changes in quadriceps femoris muscle in critically ill children using ultrasonography [J]. *Indian J Pediatr*, 2023, 90(6): 541-547
- [10] COIFFARD B, RIEGLER S, SKLAR M C, et al. Diaphragm echodensity in mechanically ventilated patients: a description of technique and outcomes [J]. *Crit Care*, 2021, 25(1): 64
- [11] FORMENTI P, UMBRELLO M, CASTAGNA V, et al. Respiratory and peripheral muscular ultrasound characteristics in ICU COVID 19 ARDS patients [J]. *J Crit Care*, 2022, 67: 14-20
- [12] HAAKSMA M E, SMIT J M, BOUSSUGES A, et al. Expert consensus on diaphragm ultrasonography in the critically ill (EXODUS): a Delphi consensus statement on the measurement of diaphragm ultrasound-derived parameters in a critical care setting [J]. *Crit Care*, 2022, 26(1): 99
- [13] IJLAND M M, VAN DOORN J L M, BEUKMAN A, et al. The effect of mechanical ventilation on respiratory muscle echogenicity in critically ill children: an observational cohort study [J]. *BMC Pediatr*, 2025, 25(1): 502
- [14] CHEN Y L, LIU P T, CHIANG H K, et al. Ultrasound measurement of rectus femoris muscle parameters for discriminating sarcopenia in community-dwelling adults [J]. *J Ultrasound Med*, 2022, 41(9): 2269-2277
- [15] BUNOUT D, GONZALEZ S, CANALES M, et al. Ultrasound assessment of rectus femoris pennation angle and echogenicity. Their association with muscle functional measures and fat infiltration measured by CT scan [J]. *Clin Nutr ESPEN*, 2023, 55: 420-424
- [16] BURNS K E A, WONG J, RIZVI L, et al. Frequency of screening and spontaneous breathing trial techniques: a randomized clinical trial [J]. *JAMA*, 2024, 332(21): 1808-1821
- [17] HEUNKS L M, VAN DER HOEVEN J G. Clinical review: the ABC of weaning failure—a structured approach [J]. *Crit Care*, 2010, 14(6): 245
- [18] VALVERDE MONTORO D, ROSA CAMACHO V, ARTACHO GONZÁLEZ L, et al. Thigh ultrasound monitoring identifies muscle atrophy in mechanically ventilated pediatric patients [J]. *Eur J Pediatr*, 2023, 182(12): 5543-5551
- [19] OIKONOMOU E, PARASKEVAS T, VELISSARIS D. Sepsis and the muscle tissue. A narrative review [J]. *Rom J Intern Med*, 2021, 59(3): 218-226
- [20] 薛秋丽,师睿渊,田冰,等.脓毒症性肌病的治疗研究进展 [J]. *中国急救医学*, 2023, 43(5): 360-364
XUE Q L, SHI R Y, TIAN B, et al. Advances in therapeutic methods of sepsis-induced myopathy [J]. *Chinese Journal of Critical Care Medicine*, 2023, 43(5): 360-364
- [21] NAKANISHI N, ONO Y, MIYAZAKI Y, et al. Sepsis causes neutrophil infiltration in muscle leading to muscle atrophy and weakness in mice [J]. *Front Immunol*, 2022, 13: 950646
- [22] GOOSSENS C, WECKX R, DERDE S, et al. Impact of prolonged sepsis on neural and muscular components of muscle contractions in a mouse model [J]. *J Cachexia Sarcopenia Muscle*, 2021, 12(2): 443-455
- [23] DRES M, DUBÉ B P, MAYAUX J, et al. Coexistence and impact of limb muscle and diaphragm weakness at time of liberation from mechanical ventilation in medical intensive care unit patients [J]. *Am J Respir Crit Care Med*, 2017, 195(1): 57-66
- [24] 陶乐,邱梦宁,赵佳琦.重症监护病房获得性肌无力的超声量化评估研究进展 [J]. *海军军医大学学报*, 2025, 46(7): 916-921
TAO L, QIU M N, ZHAO J Q. Ultrasonic quantitative assessment of intensive care unit acquired weakness: research progress [J]. *Academic Journal of Naval Medical University*, 2025, 46(7): 916-921
- [25] ALBAYDA J, VAN ALFEN N. Diagnostic value of muscle ultrasound for myopathies and myositis [J]. *Curr Rheumatol Rep*, 2020, 22(11): 82
- [26] TRUONG D, ABO S, WHISH-WILSON G A, et al. Methodological and clinimetric evaluation of inspiratory respiratory muscle ultrasound in the critical care setting: a systematic review and meta-analysis [J]. *Crit Care Med*,

2023, 51(2):e24-e36

[27] IM Y J, CHOE Y, LEE J, et al. Quantitative muscle ultrasound: a non-invasive biomarker for monitoring duchenne muscular dystrophy [J]. *Muscle Nerve*, 2025, 72(4): 606-615

[28] FU X, WANG Z, WANG L P, et al. Increased diaphragm echodensity correlates with postoperative pulmonary complications in patients after major abdominal surgery: a prospective observational study [J]. *BMC Pulm Med*, 2022, 22(1):400

[29] LIMA J, FOLETTO E, CARDOSO R C B, et al. Ultrasound for measurement of skeletal muscle mass quantity and muscle composition/architecture in critically ill patients: a scoping review on studies' aims, methods, and findings[J]. *Clin Nutr*, 2024, 43(1):95-110

[30] MOURTZAKIS M, PARRY S, CONNOLLY B, et al. Skeletal muscle ultrasound in critical care: a tool in need of translation[J]. *Ann Am Thorac Soc*, 2017, 14(10): 1495-1503

[31] TUINMAN P R, JONKMAN A H, DRES M, et al. Respiratory muscle ultrasonography: methodology, basic and advanced principles and clinical applications in ICU and ED patients-a narrative review [J]. *Intensive Care Med*, 2020, 46(4):594-605

[32] COMBET M, COMAN B, TELIAS I. Monitoring and preserving diaphragmatic function in mechanical ventilation [J]. *Curr Opin Crit Care*, 2025, 31(3): 293-301

[33] KARAPIINAR M, ATILLA AYYILDIZ V, ÜNAL M, et al. Ultrasound imaging of quadriceps muscle in patients with knee osteoarthritis: the test-retest and inter-rater reliability and concurrent validity of echo intensity measurement [J]. *Musculoskelet Sci Pract*, 2021, 56: 102453

(收稿: 2025-04-26; 修回: 2025-09-28; 录用: 2025-10-22)
(本文编辑: 戴王娟)

(上接第 230 页)

(19):2639-2642

WANG J, LIU X F, LV Y, et al. A case-control study on the risk factors for hepatitis E incidence in Baoshan District, Shanghai [J]. *Occupational and Health*, 2022, 38(19):2639-2642

[26] 唐莹, 管文齐, 王凤双, 等. 2005-2019年北京市顺义区戊型肝炎流行病学特征及危险因素分析[J]. *华南预防医学*, 2021, 47(7):926-929

TANG Y, GUAN W Q, WANG F S, et al. Epidemiological characteristics and risk factors of hepatitis E in Shunyi District, Beijing from 2005 to 2019[J]. *South China Journal of Preventive Medicine*, 2021, 47(7):926-929

[27] 艾弗. 江苏省戊型肝炎分子流行病学及全球研究趋势分析[D]. 南京: 东南大学, 2022

AI F. Molecular epidemiology of hepatitis E in Jiangsu Province and analysis of global research trends[D]. Nanjing: Southeast University, 2022

[28] 吴建平, 杨丹娇, 蓝岚, 等. 猪戊型肝炎病毒的研究进展[J]. *四川畜牧兽医*, 2022, 49(12):32-34

WU J P, YANG D J, LAN L, et al. Research progress on swine hepatitis E virus [J]. *Sichuan Journal of Animal and Veterinary Sciences*, 2022, 49(12): 32-34

[29] 蒋欣, 郑仁淑, 于世娟. 不同人群戊型肝炎血清流行病学调查[J]. *中国校医*, 2011, 25(4):282-283

JIANG X, ZHENG R S, YU S J. Serological epidemiological survey of hepatitis E in different populations [J]. *Chinese Journal of School Health*, 2011, 25(4): 282-283

(收稿: 2025-05-21; 修回: 2025-09-16; 录用: 2025-09-30)
(本文编辑: 陈汐敏)