

无创左室压力应变曲线评价血液透析对左室心肌做功的影响

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【摘要】 目的 采用无创左室压力应变曲线(pressure strain loops, PSLs)评价终末期肾脏疾病(end-stage renal disease, ESRD)患者在维持性血液透析(maintenance hemodialysis, MHD)后左室心肌做功的变化及单次血透对左室做功的影响。**方法** 连续入组维持性血液透析 ≥ 6 个月的ESRD患者92例,于非透析日采集患者二维长轴及短轴图像,其中28例患者在透析当天的透析前后30 min内再次采集图像。选取同期年龄、性别相匹配的健康志愿者40例为对照。采用PSLs进行脱机分析,获得左室整体做功指数(global work index, GWI)、整体有效功(global constructive work, GCW)、整体无效功(global wasted work, GWW)、整体做功效率(global work efficiency, GWE)及整体长轴应变(global longitudinal strain, GLS)。**结果** 两组比较:MHD组GWE显著低于对照组($P < 0.001$), GWW显著高于对照组($P < 0.001$)。透析前后比较:透析后GWI($P < 0.001$)、GCW($P = 0.002$)、GWE($P = 0.037$)、GLS($P < 0.001$)均显著降低, GWW差异无统计学意义($P = 0.892$)。相关性研究结果:左室质量指数(left ventricular mass index, LVMI)与GWE、GWW、GLS具有相关性(GWE: $r = -0.546$; GWW: $r = 0.438$; GLS: $r = 0.559$; P 均 < 0.001)。MHD患者超滤量与透析前后GWI及GCW差值具有相关性(GWI差值: $r = 0.547$, $P = 0.003$; GCW差值: $r = 0.500$, $P = 0.009$)。**结论** PSLs结合后负荷和应变指标能敏感评估ESRD患者长期血液透析后心肌做功的改变及单次透析对心肌做功指标的影响。

【关键词】 超声心动图描记术; 血液透析; 心肌做功; 应变

【中图分类号】 R540.4+5 **【文献标志码】** A **doi:** 10.3969/j.issn.1672-8467.2022.01.004

Evaluation of left ventricular myocardial work in patients with maintenance hemodialysis using non-invasive left ventricular pressure-strain loops

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【Abstract】 Objective To evaluate the impact of single and longterm maintenance hemodialysis (MHD) on left ventricular myocardial work by non-invasive left ventricular pressure strain loops (PSLs). **Methods** Ninety-two MHD patients and 40 matched controls were enrolled in the study. Conventional echocardiography was performed on the non-dialysis day. Among them, 28 MHD patients performed the echocardiography before and shortly after one hemodialysis session. Global longitudinal strain (GLS) and

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MW [Global work index (GWI), global constructive work (GCW), global work efficiency (GWE), global wasted work (GWW)] were estimated by left ventricle pressure strain curve. **Results** MHD patients performed a significantly reduced GWE ($P<0.001$) and elevated GWW ($P<0.001$) compared with healthy individuals. In 28 MHD patients, GWI ($P<0.001$), GCW ($P=0.002$), GWE ($P=0.037$) and GLS ($P<0.001$) were significantly reduced after one session of hemodialysis, while GWW ($P=0.892$) showed no statistical difference. Linear correlation analysis showed that left ventricular mass index (LVMI) was correlated with GWE, GWW and GLS (GWE: $r=-0.546$; GWW: $r=0.438$; GLS: $r=0.559$; $P<0.001$). Ultrafiltration volume was related with difference of GWI and GCW before and after hemodialysis (difference of GWI $r=0.547$, $P=0.003$; difference of GCW: $r=0.500$, $P=0.009$). **Conclusion** The non-invasive left ventricular pressure-strain loops combined with afterload and strain may be used to sensitively evaluate the myocardial work after long-term hemodialysis in ESRD Patients and the effect of one session of hemodialysis on myocardial work.

【Key words】 echocardiography; maintenance hemodialysis; myocardial work; strain

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终末期肾脏疾病(end-stage renal disease, ESRD)患者在维持性血液透析(maintenance hemodialysis, MHD)时发生心肌顿抑,导致心血管疾病的发生率和死亡率均较高^[1-2],早期发现和干预对预防不良心血管事件(cardiovascular events, CVE)至关重要。基于二维斑点追踪技术的心肌应变指标可为该类患者左心室亚临床心肌功能损伤提供敏感的检测方法^[3],左室整体纵向应变(global longitudinal strain, GLS)是MHD患者CVE的独立预测因子^[4],但其主要局限性为负荷依赖性,后负荷的增加可使应变降低,因而影响心肌功能评估的准确性^[5]。近年来基于无创左室压力应变曲线(pressure strain loops, PSLs)的心肌做功(myocardial work, MW)指标结合血压和应变,是评估左室心肌性能的新方法^[6-7]。研究表明,在鉴别急性冠脉综合征时, MW参数优于左室射血分数(left ventricular ejection fraction, LVEF)和GLS,是室壁运动无异常和LVEF正常的冠心病患者最敏感的预测因子,同时也为纠正心室收缩不同步和预测心脏再同步化治疗的疗效提供了额外信息^[6, 8-10]。本研究旨在探讨MW指标评估ESRD患者长期透析及单次透析对心肌做功的影响。

资 料 和 方 法

研究对象 2015年4月至2016年6月连续入组

92例于复旦大学附属中山医院进行血液透析的ESRD患者(MHD组),血液透析时间 ≥ 6 个月,平均 (30 ± 12) 个月。其中男性57例,女性35例,平均年龄为 (57.2 ± 12.3) 岁。排除标准:先天性心脏病;严重的瓣膜狭窄或关闭不全;室壁运动异常;LVEF $<50\%$;心律失常;中度以上肺动脉高压;中等量以上心包积液;无法获得满意的超声二维图像。在92例入组患者中,72例为慢性肾小球肾炎,6例为IgA肾病,4例为多囊肾病,10例为糖尿病肾病。对照组为同期40例健康志愿者,与MHD组年龄、性别相匹配,男性24例,女性16例,平均年龄为 (53.9 ± 12.1) 岁。无心脏症状、高血压、糖尿病史,体检正常,心电图、超声心动图及血生化指标正常,无用药史。本研究为前瞻性研究,经复旦大学附属中山医院伦理委员会批准(批件号:B2013-139),所有受试者均签署知情同意书。

仪器和方法

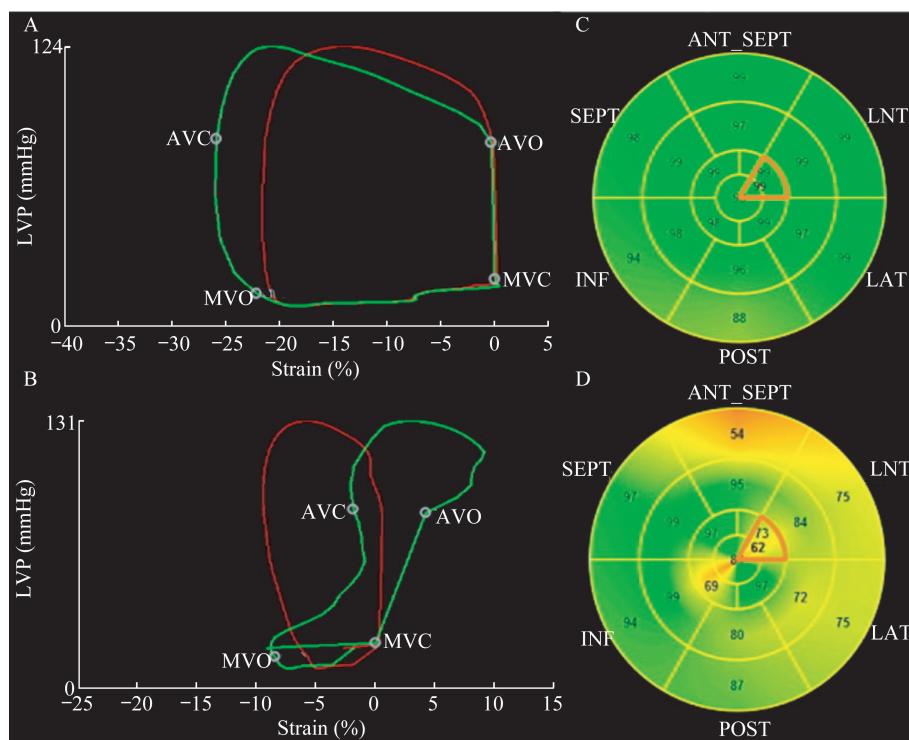
临床资料采集 采集患者的身高、体重、心率、计算体表面积(body surface area, BSA): $BSA (m^2) = 0.006 1 \times \text{身高} (cm) + 0.012 4 \times \text{体重} (kg) - 0.009 9$ 。查阅病史资料,获得高血压、糖尿病、高脂血症病史、吸烟史,用药及检验数据。采用臂式电子血压计于常规二维图像采集前后分别采集患者血压,患者取坐位,右手肘与心脏齐平,套入袖带,袖带下缘距肘窝宽2~3 cm,袖带松紧以放入一指为宜,在平静呼吸状态下记录舒张压与收缩压,取两次血压平均值。

仪器 GE Vivid E9 彩色多普勒超声仪, M5S 探头, 频率 1.7~3.3 MHz, 帧频 50~80 帧/s, 配以 EchoPAC 203 工作站。

常规二维图像采集和分析 在非透析日采集 92 例患者二维长轴及短轴图像, 其中 28 例患者另在透析当天透析前后 30 min 再次采集图像。于胸骨旁长轴切面测量左室舒张末内径(left ventricular end diastolic dimension, LVEDD)、左室收缩末内径(left ventricular end systolic dimension, LVESD)、室间隔厚度(inter-ventricular septal thickness, IVST)和后壁厚度(post wall thickness, PWT), 计算左心室质量指数(left ventricular mass index, LVMI)。于心尖四腔心切面, 采用脉冲多普勒获取二尖瓣口血流舒张早期峰值速度(E)、舒张晚期峰值速度(A), 计算 E/A 值; 在组织多普勒(tissue Doppler imaging, TDI)模式下, 将取样容积置于左室侧壁, 获取舒张早期组织运动速度(e'), 计算 E/ e' 值。于心尖四腔及二腔切面使用 Simpson's 法测量左室舒张末容积(left ventricular end diastolic volume, LVEDV)、收缩末容积(left ventricular end systolic volume, LVESV), 计算 LVEF。嘱受检者平静呼吸

后屏气, 留取清晰的左室心尖四腔、三腔、两腔切面动态图像, 连续 5 个心动周期, 存储图像以待后期分析。所有切面采集及参数测量方法均参考 2019 年美国超声心动图学会成人经胸超声心动图指南^[11]。

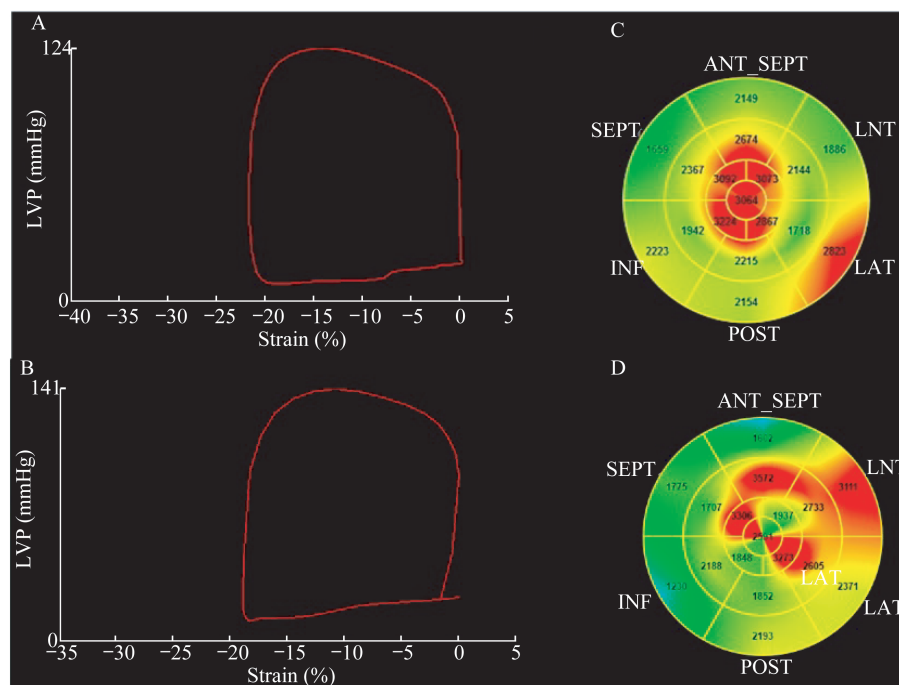
脱机图像分析 将原始数据导入 EchoPAC 203 工作站中, 进入 Q-Analysis 模式, 首先点击 Event Timing, 设定二尖瓣和主动脉瓣的开放和关闭时间。分别在左室心尖四腔、三腔、两腔切面依次手动勾画心内膜面, 软件自动生成环状感兴趣区, 手动调整心内膜、心外膜边缘使其与心肌厚度一致, 追踪满意后点击 Approve, 自动获得左心室相应切面的应变曲线, 读取数据并记录整体 GLS。输入收缩压及舒张压, 获取左室整体做功指数(global work index, GWI)、整体有效功(global constructive work, GCW)、整体无效功(global wasted work, GWW)及整体做功效率(global work efficiency, GWE)^[10,12] (图 1~3)。GWI 是从二尖瓣关闭到二尖瓣开放期间 PSLs 下的总做功。GCW 是左室收缩期心肌缩短或等容舒张期心肌延长期间的做功。GWW 是收缩期心肌伸长或等容舒张期心肌缩短所做的功。GWE 是 GCW 与 GCW 和 GWW 之和的百分比^[8]。



GMW is represented in red, and regional work segment is represented in green. PSLs and segmental bull's-eye GWE plot from normal group (A, C) and MHD patients (B, D). On the bull's-eye plot, there is significant reduction in regional GWE demonstrated as yellow-coded areas.

图 1 对照组和 MHD 组左室压力应变曲线及做功效率牛眼图

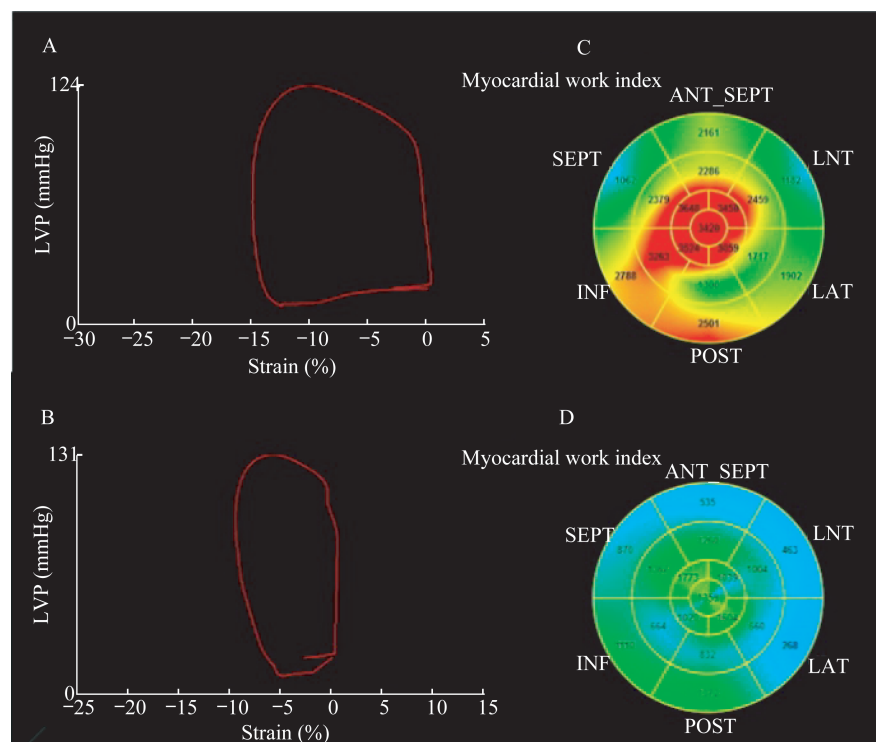
Fig 1 Left ventricular PSLs and segmental bull's-eye GWE plot from control subjects and MHD patients



The area within the red loop is estimated as global myocardial work index (GWI). PSLs and segmental bull's-eye MW plot from normal group (A, C) and MHD patients (B, D).

图2 对照组和MHD组左室PSLs及做功指数牛眼图

Fig 2 Left ventricular PSLs and segmental bull's-eye GWI plot from control subjects and MHD patients



PSLs and segmental bull's-eye MW plot before (A) and after (B) one session of hemodialysis. On the bull's-eye plot, there is significant reduction in regional MW demonstrated as blue-coded areas.

图3 透析前后左室压力应变曲线及做功指数牛眼图

Fig 3 Left ventricular PSLs and segmental bull's-eye GWI plot in MHD patients before and after one session of hemodialysis

重复性检验 对20例患者的左室做功指标及GLS进行重复性检验。观察者内差异为同一观察者间隔24 h以上两次测量的结果比较,观察者间差异为两位独立的观察者各自测量的结果比较。观察者内和观察者间的变量通过组内相关系数(intraclass correlation coefficient, ICC)分析计算。

统计学方法 采用SPSS 22.0软件进行统计分析,计量数据用 $\bar{x} \pm s$ 表示,正态分布数据组间比较采用独立样本 t 检验,非正态分布数据组间比较采用秩和检验。血透前后数据比较采用配对样本 t 检验。各变量间相关性采用Pearson线性相关分析。 $P < 0.05$ 为差异有统计学意义。

结 果

临床数据及常规超声心动图参数比较 对照组与MHD组的临床基本数据比较见表1。与对照组相比,MHD组心率、收缩压和舒张压均较高(P 均 < 0.05)。MHD组高血压、糖尿病等慢性病史及用药史的比例明显高于对照组。MHD组LVEDD、LVESD、IVST、PWT、LVMI、LVEDV、LVESV及 E/e' 均高于对照组(P 均 < 0.05),而 E/A 和 e' 低于对照组(P 均 < 0.05)。两组间LVEF和S差异无统计学意义(表2)。

表1 对照组和MHD组一般临床资料比较

Tab 1 Baseline patient characteristics between control and MHD groups

[$n(\%)$ or ($\bar{x} \pm s$)]

| Variable | Control group ($n=40$) | MHD group ($n=92$) | t/χ^2 | P |
|--------------------------|--------------------------|----------------------|------------|------------------|
| Demographic data | | | | |
| Age (y) | 53.9 ± 12.1 | 57.2 ± 12.3 | 1.195 | 0.235 |
| Male | 24 (60.0) | 57 (61.9) | 0.045 | 0.832 |
| BSA (m^2) | 1.77 ± 0.18 | 1.74 ± 0.19 | -0.776 | 0.439 |
| Heart rate (beats/min) | 66.1 ± 9.0 | 77.0 ± 11.4 | 4.404 | <0.001 |
| Systolic BP (mm Hg) | 118.4 ± 15.9 | 145.8 ± 20.4 | 6.181 | <0.001 |
| Diastolic BP (mm Hg) | 76.0 ± 9.0 | 82.3 ± 11.8 | 2.453 | 0.016 |
| CV risk factors | | | | |
| Hypertension | 0 | 85 (92.4) | 103.793 | <0.001 |
| Diabetes mellitus | 0 | 17 (18.5) | 8.484 | <0.001 |
| Hypercholesterolemia | 4 (10.0) | 18 (19.6) | 1.837 | 0.159 |
| Coronary heart disease | 0 | 12 (13.0) | 5.739 | 0.002 |
| Current smoking | 5 (12.5) | 24 (26.1) | 3.002 | 0.071 |
| Cardiovascular event | 0 | 27 (29.3) | 14.758 | <0.001 |
| Medications | | | | |
| ACEI/ARB | 0 | 36 (39.1) | 21.522 | <0.001 |
| β -blocker | 0 | 49 (53.3) | 33.882 | <0.001 |
| CCB | 0 | 14 (15.2) | 6.809 | 0.001 |
| Statin | 0 | 12 (13.0) | 5.739 | 0.002 |
| Laboratory index | | | | |
| BUN (mmol/L) | 4.4 ± 1.6 | 28.6 ± 5.7 | 20.359 | <0.001 |
| Cr ($\mu\text{mol/L}$) | 66.1 ± 12.1 | 1115.6 ± 267.8 | 19.131 | <0.001 |
| BNP (pg/mL) | 28.8 ± 19.4 | 350.4 ± 48.8 | 33.674 | <0.001 |

MHD: Minitenance hemodialysis; BSA: Body surface area; BP: Blood pressure; CV: Cardiovascular; ACEI: Angiotensin-converting enzyme inhibitors; ARB: Angiotensin receptor blockers; CCB: Calcium channel blocker; BUN: Blood urea nitrogen; Cr: Creatinine; BNP: Brain natriuretic peptide.

表2 对照组和MHD组常规心超参数比较

Tab 2 Conventional echocardiographic parameters between control and MHD groups ($\bar{x} \pm s$)

| Parameters | Control group (n=40) | MHD group (n=92) | t | P |
|----------------------------|----------------------|------------------|--------|------------------|
| LVEDD (mm) | 45.5 ± 3.8 | 48.8 ± 5.5 | 2.872 | 0.005 |
| LVEDS (mm) | 28.5 ± 2.8 | 31.0 ± 4.8 | 2.519 | 0.013 |
| IVST (mm) | 8.6 ± 1.0 | 10.9 ± 1.5 | 7.297 | <0.001 |
| PWT (mm) | 8.3 ± 1.0 | 10.6 ± 1.5 | 7.119 | <0.001 |
| LVMI (g/m ²) | 80.1 ± 16.7 | 131.8 ± 37.6 | 6.669 | <0.001 |
| LVEDV (mL/m ²) | 39.3 ± 8.1 | 55.6 ± 15.0 | 5.181 | <0.001 |
| LVESV (mL/m ²) | 12.9 ± 3.7 | 19.7 ± 8.4 | 3.937 | <0.001 |
| LVEF (%) | 67.7 ± 4.9 | 65.1 ± 6.8 | -1.800 | 0.075 |
| E/A | 1.2 ± 0.5 | 0.8 ± 0.3 | -5.903 | <0.001 |
| S (cm/s) | 10.3 ± 3.2 | 9.7 ± 1.8 | -0.850 | 0.403 |
| e' (cm/s) | 11.2 ± 3.6 | 8.3 ± 2.2 | -4.998 | <0.001 |
| E/e' | 6.7 ± 1.4 | 8.8 ± 3.1 | 3.283 | <0.001 |

LVEDD/ESD: Left ventricular end-diastolic dimension/end-systolic dimension; IVST: Interventricular septum thickness; PWT: Posterior wall thickness; LVMI: Left ventricular mass index; LVEDV/ESV: Left ventricular end diastolic volume/end systolic volume; LVEF: Left ventricular ejection fraction; E: Early transmitral flow velocity; A: Late transmitral flow velocity; e': Mean peak early diastolic myocardial annular velocity.

二维斑点追踪显像做功参数比较 MHD组GWE、GLS显著低于对照组($P<0.001$,图1),GWW显著高于对照组($P<0.001$),GWI和GCW差异无统计学意义(表3,图2)。透析前后比较,透析后GWI($P<0.001$)、GCW($P=0.002$)、GWE($P=0.037$)及GLS($P<0.001$)均显著降低,GWW($P=0.892$)的差异无统计学意义(表4,图3)。

表3 对照组和MHD组做功参数及GLS比较

Tab 3 MW and GLS parameters between control and MHD groups ($\bar{x} \pm s$)

| Parameters | Control group (n=40) | MHD group (n=92) | t | P |
|-------------|----------------------|------------------|--------|------------------|
| GWI (mmHg%) | 1 999.7 ± 310.5 | 2 118.9 ± 463.5 | -1.618 | 0.109 |
| GCW (mmHg%) | 2 176.5 ± 308.7 | 2 290.6 ± 441.7 | -1.590 | 0.116 |
| GWE (%) | 94 ± 2.3 | 91 ± 4.2 | 4.226 | <0.001 |
| GWW (mmHg%) | 110.3 ± 58.3 | 163.1 ± 88.2 | -3.792 | <0.001 |
| GLS (%) | -20.1 ± 2.4 | -16.2 ± 3.2 | -7.268 | <0.001 |

GWI: Global work index; GCW: Global constructive work; GWE: Global work efficiency; GWW: Global wasted work; GLS: Global longitudinal strain.

表4 MHD组透析前后做功参数及GLS比较

Tab 4 Comparison of MW and GLS in MHD group before and after one session of hemodialysis ($\bar{x} \pm s$)

| Parameters | Pre-MHD (n=28) | Post-MHD (n=28) | t | P |
|-------------|-----------------|-----------------|--------|------------------|
| GWI (mmHg%) | 2 172.6 ± 474.1 | 1 746.6 ± 579.2 | 4.237 | <0.001 |
| GCW (mmHg%) | 2 295.1 ± 479.4 | 1 945.3 ± 567.5 | 3.455 | 0.002 |
| GWE (%) | 91.7 ± 3.6 | 90.1 ± 4.5 | 2.203 | 0.037 |
| GWW (mmHg%) | 167.3 ± 74.6 | 169.4 ± 77.7 | -0.137 | 0.892 |
| GLS (%) | -16.9 ± 3.1 | -14.7 ± 4.2 | -4.543 | <0.001 |

GWI: Global work index; GCW: Global constructive work; GWE: Global work efficiency; GWW: Global wasted work; GLS: Global longitudinal strain.

相关性研究结果显示,MHD患者GWW、GLS与LVMI呈正相关(GWW: $r=0.438$; GLS: $r=0.559$, P 均 <0.001),GWE与LVMI呈负相关($r=-0.546$, $P<0.001$)。透析前后GWI及GCW差值与患者超滤量呈正相关(GWI差值: $r=0.524$, $P=0.005$; GCW差值: $r=0.544$, $P=0.004$;图4)。

做功参数重复性检验 左室做功指标GWI、GCW、GWE、GWW和GLS的观察者内ICC值分别为0.93、0.90、0.85、0.90和0.89,观察者间ICC值分别为0.96、0.96、0.83、0.77和0.95,提示由PSLs估测的做功指标重复性良好。

讨 论

血液透析作为一项重要的肾脏替代治疗手段,能清除ESRD患者体内的肾脏毒素和多余体液,降低心脏负荷,使患者的死亡率显著降低;但透析后患者心血管疾病的发病率较高,也是造成患者死亡的主要原因^[13]。研究显示,GLS作为预测MHD患者心血管事件的敏感指标之一,即使在LVEF正常的患者中也会显著降低^[4]。然而,MHD患者后负荷的变化会影响左室收缩和心肌张力,削弱了GLS评估其收缩功能的能力^[14];另一方面,MHD患者GLS的普遍改善将减少个体间的差异^[7]。因此不同阶段ESRD患者心肌细微形变异常的差异可能会减小,对应变的预后价值产生不利影响。Russel等^[10]通过对应变曲线进行微分计算节段缩短率,并与左室瞬时压力相乘来量化心肌做功,能够更直观及准确地反映心肌运动和代谢情况^[15]。研究表明,对于心脏再同步化治疗者,PSLs可提供更多关于左室收缩不

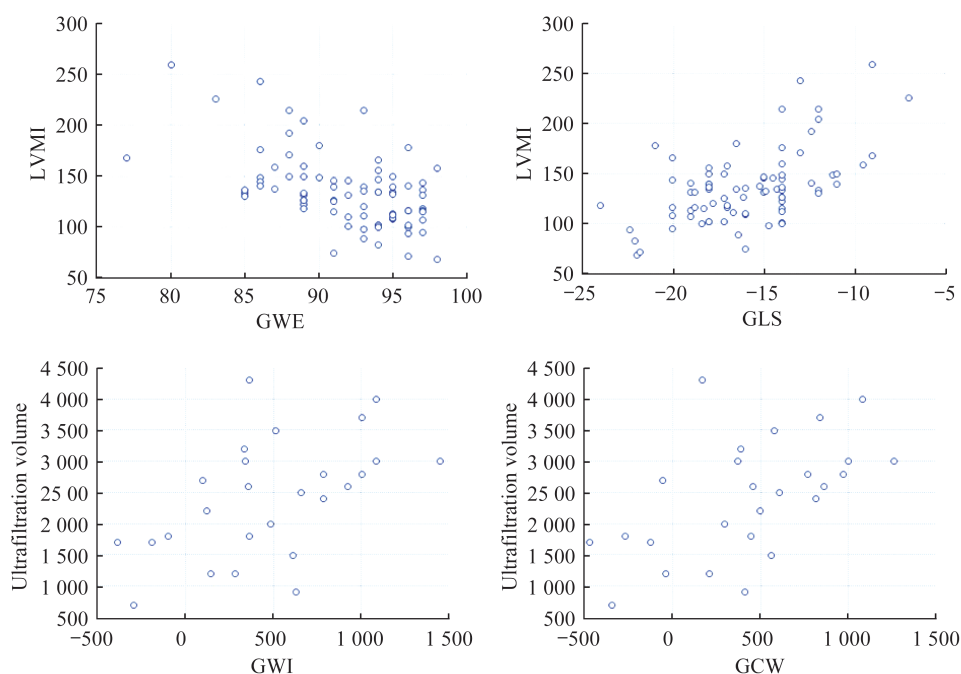


图4 做功参数与左室质量指数及超滤量相关性的散点图

Fig 4 Scatter plot of MW parameters with LVMI and ultrafiltration volume

同步、节段性运动和心肌收缩力的额外信息^[16]。MW也被证明在非ST段抬高的急性冠状动脉综合征患者中可识别急性冠脉闭塞^[17]。

本研究结果显示,与对照组相比,MHD组GWW显著升高,GWE降低,GWI和GCW无明显变化。ERSD患者肾素-血管紧张素系统活性增高,血管舒张物质减少,导致后负荷增加。因此,虽然ESRD患者GLS降低,但由于克服后负荷做功更多,MHD组GWI和GCW无明显变化。虽然本研究纳入的患者LVEF均 $\geq 50\%$,但ESRD本身对心肌的损害使左室心肌收缩不同步,长期透析又使左室收缩及舒张功能均减退,增加了心肌代偿运动能量的损耗,且透析过程中可能由于间断性血容量减少而产生一过性低血压^[18],患者血压状态波动较大,心脏后负荷增加和不稳定的血流动力学状态均可致GWW明显增加。ESRD患者长期透析后,左室收缩不同步程度加重,GLS进一步降低,GWW升高,此结果与文献^[19]一致。研究显示,心梗后患者和心衰患者的GWE显著降低^[20]。Vander等^[9]研究发现,心衰患者心脏再同步化治疗前的低GWE与良好长期预后独立相关。

与透析前相比,透析后30 min内GWI、GCW、GWE、GLS均显著降低。单次血液透析对心脏功

能的影响存在争议。有研究显示单次透析后左室应变显著改善,也有研究证实反复透析后心肌整体和节段性收缩功能减退。对于个体而言,在体内代谢机制正常的情况下,血透可移除体内多余的液体,前负荷降低可能使左室收缩增强、应变增加,同时血透也可清除大量肾毒素,对心肌细胞有益。然而肾功能不全患者在早期即可发生心肌损害,心肌的代偿能力较弱,短期内大量液体快速移除可使血压波动、心输出量降低、心肌血流灌注下降,造成心肌细胞损伤和顿抑,导致左室收缩功能和应变降低。应变和血压的双重下降使GWI和GCW较透析前显著降低。GCW降低,GWW维持稳定,因此透析后患者GWE降低,这提示单次透析本身对ESRD患者心肌细胞的损伤可能大于获益。Ingec等^[21]也证实,在65%的患者中单次血液透析后心肌损伤标志物cTnI增加。另外,透析过程中维持血压稳定,既需要心脏泵血功能的调整,也需要外周血管的舒缩调节,血压大幅度波动说明患者的心脏和外周血管的代偿调节能力下降,同时也对心脏和血管本身产生更明显的损伤作用,两者互为因果造成恶性循环。

ESRD患者由于长期容量及压力负荷过重,导致心肌发生重构,包括心腔增大、室壁肥厚、心肌纤

维化及左室质量增加。本研究结果提示,LVMI越大,患者所作无用功越多,做功效能及应变越低,提示做功指标或能反映心室重构的严重程度。透析前后GWI及GCW差值与MHD患者超滤量呈正相关,说明透析量越大,透析后心肌整体做功减少越多,这提示单次透析后患者可产生一过性心肌顿抑,减少超滤量可能会有保护心肌细胞的作用。

本研究的局限性在于:(1)透析前后病例数较少;(2)未对患者跟踪随访,以充分探讨做功参数的预测价值;(3)仅限于左室心肌整体做功研究,各阶段做功的差异有待进一步探讨。

综上所述,无创左室PSLs同时将后负荷和应变指标纳入计算,或能更准确敏感地评估MHD患者透析后心肌性能的变化,为量化心肌收缩功能和研究心肌力学提供了更客观的指标。

作者贡献声明 郭瑶 实验设计和实施,数据采集和分析,论文撰写,图表制作。邢雨蒙 实验实施,数据采集和分析。曹学森 数据采集,材料准备。潘翠珍,舒先红 材料准备,实验指导。孙敏敏 实验设计,数据采集,论文修订。

利益冲突声明 所有作者均声明不存在利益冲突。

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