基于 UHPLC-Q-TOF-MS 技术探究脾肾两助丸钴-60 辐照灭菌前后化学差异

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摘要：目的 辐照灭菌广泛应用于中药制剂领域，但辐照灭菌对中药化学组成是否产生影响需要深入研究，尤其是针对组方复杂的丸剂类中成药。**方法** 本研究以处方 30 味药材的脾肾两助丸为例，首先采用超高效液相色谱-四极杆飞行时间质谱（UHPLC-Q-TOF-MS）高分辨质谱技术对脾肾两助丸化学成分进行解析，然后利用所得到的数据对脾肾两助丸成分进行多元统计分析，最后对比《中国药典》2020 年版中 15 味药 22 个指标成分辐照前后的含量，同时分析其余质谱鉴定化合物的差异，全面探究辐照灭菌化学差异。**结果** 共鉴定出 260 个化合物，包括 45 个黄酮类化合物，28 个三萜类化合物，24 个苯丙素类化合物以及糖苷类、有机酸类、脂类、氨基酸类、生物碱类等其他类化合物 163 个。主成分分析、聚类分析均表明脾肾两助丸在钴-60 辐照［剂量（2.5 ± 0.5）kGy］前后整体化学组成没有显著差异，所鉴定的成分中仅有 13 个成分发生变化，且变化率较小。**结论** 钴-60 辐照灭菌对脾肾两助丸整体化学组成影响不大。本研究以脾肾两助丸为例，证明了高分辨质谱在中药辐照灭菌所致化学差异研究中的应用前景，也为辐照灭菌技术在中成药生产中的应用提供了科学依据。

关键词：高分辨质谱；脾肾两助丸；钴-60 辐照灭菌；化学差异

doi：10.11669/cpj.2025.04.009　　**中图分类号：**R917　　**文献标志码：**A　　**文章编号：**1001－2494（2025）04－0394－13

Investigation of Chemical Differences between Pishenliangzhu Pills before and after Sterilization by Cobalt-60 Irradiation Based on UHPLC-Q-TOF-MS Technique

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ABSTRACT: OBJECTIVE To investigate the effect of this tratitional Chinese medicine irradiation sterilization on the chemical composition, especially pills with complex herb composition. **METHODS** The chemical composition of Pishenliangzhu Pills was examined using high-resolution mass spectrometry. Then, the obtained data were used for the multivariate statistical analysis of the components of Pishenliangzhu Pills and finally, the contents of 22 index components of 15 medicines in the Chinese Pharmacopoeia 2020 were compared before and after irradiation, and the rest of the compounds were analyzed by mass spectrometry, so as to comprehensively investigate the differences in the chemistry of the irradiated sterilizers. **RESULTS** A total of 260 compounds were identified, including 45 flavonoids, 28 triterpenoids, 24 phenylpropanoid compounds, and 163 glycosides, organic acids, lipids, amino acids, and alkaloids. Principal component analysis and cluster analysis revealed that there were no significant changes in the chemical composition of Pishenliangzhu Pills after Cobalt-60 irradiation at a dose of (2.5 ± 0.5) kGy, with only 13 components showing minor alterations. **CONCLUSION** This study demonstrates the potential of high-resolution mass spectrometry in investigating chemical differences induced by irradiation sterilization in traditional Chinese medicine using Pishenliangzhu Pills as an example, which providing scientific evidence for the utilization of irradiation sterilization technology in producing Chinese patent medicines.

KEY WORDS: high resolution mass spectrometry; Pishenliangzhu Pills; Cobalt-60 irradiation sterilization; chemical difference

脾肾两助丸由党参 164 g、熟地黄 340 g、酒萸肉 180 g、麸炒山药 180 g、炙黄芪 180 g、酒白芍 180 g、泽泻 180 g、陈皮 46 g、盐小茴香 180 g、盐补骨脂 46 g、茯苓 90 g、枸杞子 46 g 等 30 味中药组成，主要功效有健脾益气、滋补肝肾。用于脾肾虚弱而致的肢体倦怠、气虚无力、不思饮食、胃脘痞闷、腰痛腰困、腿膝疲软及头晕耳鸣[1]。

辐照灭菌主要是利用电离辐射（主要是指 ^{60}Coγ 射线、加速器产生的电子束或 X 射线）与物质的相互作用所产生的物理、化学和生物效应。其原理是破坏微生物细胞中的 DNA 和 RNA，使受损的 DNA 和 RNA 发生降解，失去合成蛋白质和遗传功能，从

基金项目：国家中医药管理局青年岐黄学者培养项目资助（2022-256）

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而达到杀灭细胞的作用[2]。与传统的灭菌方法如高压灭菌、湿热灭菌、干热灭菌、微波灭菌[3]相比，辐照灭菌不会升高被辐照药物的温度，是热敏性药物的最佳灭菌方法。而且由于辐照灭菌具有穿透力强、操作简便、速度快、常温常压等优势，目前广泛用于中药材及其制剂的灭菌[4]。但当辐照剂量超过一定范围时，中药材及其制剂的有效成分会有损失，影响其药用质量[5]。为指导和规范辐照技术在中药灭菌中的正确应用，保证中药药品质量，原国家食品药品监督管理总局在2015年组织制定了《中药辐照灭菌技术指导原则》[6]。在中药及其制剂的领域中，辐照灭菌作为一种常见的灭菌方法，其对药物的影响一直是研究的重点。已有研究大多采用液相含测或指纹图谱方法分析辐照灭菌对中药化学组成的影响[7-8]。但中药是典型的化学复杂体系，液相方法仅能针对有限的指标成分进行分析，无法全面评价辐照灭菌对中药化学组成的影响。液质联用技术作为一种先进的分析手段，结合了液相色谱的分离能力和质谱的高灵敏度鉴定特性，能够提供更丰富的成分信息。液质联用技术因其具有选择性强、灵敏度高、分离度高等优势，可实现复杂样品的快速分离和多组分的准确定性分析。近年来广泛用于中药的定性定量分析[9]。因此，借助液质联用技术，可以更全面地研究辐照灭菌对中药及其制剂的影响。

本研究首先基于超高效液相色谱-四极杆飞行时间质谱（UHPLC-Q-TOF-MS）高分辨质谱技术对脾肾两助丸粉化学成分进行解析，然后对（2.5 ± 0.5）kGy辐照剂量下脾肾两助丸粉化学成分灭菌前后进行比较，并结合多元统计分析，对脾肾两助丸辐照灭菌前后的差异化学成分进行全面分析。

1 材 料

1.1 仪器

Agilent 1260型高效液相色谱仪（包括四元泵、柱温箱、自动进样器、DAD检测器和OpenLAB工作站）、Agilent 1290型超高效液相色谱仪（美国Agilent公司）；AB SCIEX LC-Q-TOF 5600 + 型质谱仪（美国AB SCIEX公司）；CP214型万分之一电子天平（奥豪斯有限公司）；UPT-Ⅱ-20T型超纯水器（四川优普超纯科技有限公司）；KQ5200E型超声波清洗仪（昆山市超声仪器有限公司）。

1.2 试剂与样品

实验用脾肾两助丸原料粉（批号：Q202208001-Q202208006，Q202209001-Q202209004，华康药业）；质谱级甲醇、质谱级乙腈、色谱级甲醇、色谱级乙腈（美国赛默飞世尔科技有限公司）；质谱级甲酸、甲酸（天津市大茂化学试剂厂）；娃哈哈纯净水，屈臣氏饮用水，其他试剂均为分析纯。对照品：党参炔苷（批号：111732-201908）、绿原酸（批号：110753-201716）、黄芪甲苷（批号：110781-202118）、芍药苷（批号：110735-202145），地黄苷D（批号：112063-202103），莫诺苷（批号：111998-202104）、马钱苷（批号：111640-201808）、松脂醇二葡萄糖苷（批号：111537-202107）、补骨脂素（批号：110739-201918）、异补骨脂素（批号：110738-202016），橙皮苷（批号：110721-202019），款冬酮（批号：111884-202105），β蜕皮甾酮（批号：111638-201907），松果菊苷（批号：111670-201907）、毛蕊花糖苷（批号：111530-201914），甘草苷（批号：111610-201908）、甘草酸（批号：110731-202021）、23-乙酰泽泻醇B（批号：111846-202006）、23-乙酰泽泻醇C（批号：112062-202102）、阿魏酸（批号：0773-9910）（纯度均 > 98%，中国食品药品检定研究院）；新绿原酸（批号：PS000974）、隐绿原酸（批号：PS001110）、异绿原酸A（批号：PS012051）、芒柄花苷（批号：PS000671）、甘草素（批号：PS021113）（纯度均 > 98%，成都普思生物科技股份有限公司）；芦丁（批号：HR17513B1）、异甘草苷（批号：HI5423S1）（宝鸡市辰光生物有限公司，纯度 > 98%）；白术内酯Ⅱ（批号：wkq23031609）、白术内酯Ⅲ（批号：wkq23051202）（纯度均 > 98%，四川省维克奇生物科技有限公司）；琥珀酸（批号：2939）、茯苓酸A（批号：7419）（上海诗丹德标准技术服务有限公司，纯度均 > 98%）；异绿原酸B（批号：102776，江苏永健医药科技有限公司，纯度 > 98%）。

2 脾肾两助丸高效液相色谱图的建立

2.1 供试品溶液制备

称取脾肾两助丸原料粉末适量，研细，取约1.00 g，精密称定，置圆底烧瓶中，精密加入体积分数60%甲醇20 mL，密塞，称定质量，80 ℃回流处理1 h，放冷，再称定质量，用体积分数60%甲醇补足减失的重量，摇匀，滤过，取续滤液，即得供试品溶液。

2.2 色谱条件

Waters Symmetry C_{18}色谱柱（4.6 mm × 250 mm，5 μm）；流动相为乙腈（A）-体积分数0.1%甲酸水（B）溶液；梯度洗脱条件：0 ~ 12 min，2% ~ 10% A；12 ~ 15 min，10% ~ 15% A；15 ~ 22 min，15% ~ 20% A；

22 ~ 24 min, 20% A; 24 ~ 29 min, 20% ~ 25% A; 29 ~ 31 min, 25% A; 31 ~ 36 min, 25% ~ 45% A; 36 ~ 41 min, 45% ~ 60% A; 41 ~ 53 min, 60% ~ 63% A; 53 ~ 63 min, 63% ~ 90% A; 流速 1 mL · min^{-1}; 柱温 25 ℃; 进样体积 10 μL。DAD 全波长扫描。

2.3 基于液质联用技术探究脾肾两助丸灭菌前后化学差异

2.3.1 供试品溶液制备 称取灭菌前后脾肾两助丸原料粉末约 0.3 g, 置于玻璃离心管中, 加入 6 mL 体积分数 60% 甲醇, 超声提取 1 h, 以 3 500 r · min^{-1} 离心 10 min, 静置后取上清液过 0.22 μm 微孔滤膜后, 置于 4 ℃冰箱中备用; 取每个样品溶液8 μL合并, 作为质控样本, 用于检测仪器分析方法的稳定性。

2.3.2 色谱条件 样品的分离采用 Waters Acquity UHPLC HSS T3 色谱柱 (2.1 mm × 100 mm, 1.8 μm), 柱温设置为 35 ℃; 流动相由体积分数 0.1% 甲酸水溶液 (A)-乙腈 (B) 组成, 梯度洗脱: 0 ~ 9 min, 2% ~ 25% B; 9 ~ 17 min, 25% ~ 60% B; 17 ~ 22 min, 60% ~ 65% B; 22 ~ 27 min, 65% ~ 90% B; 27 ~ 28 min, 90% ~ 2% B; 28 ~ 32 min, 2% B, 进样体积为 3 μL, 流速为 0.3 mL · min^{-1}。

2.3.3 质谱条件 电喷雾离子源 (ESI), 采用正负离子模式分别扫描, 离子源参数: 喷雾电压 -4 500 V (负离子)、5 500 V (正离子), 离子源温度 500 ℃, 喷雾气 (Gas 1) 379.225 kPa, 加热气 (Gas 2) 379.225 kPa, 气帘气 (CUR) 206.85 kPa, 去簇电压 (DP) 60 V, 二级碰撞能量 (CE) 为 40 eV, CEs 为 20 eV。二级质谱采用数据非依赖采集 (IDA) 获得, 选择响应值最高的 10 个质谱碎片进行二级质谱扫描, TOF MS 一级扫描范围为 *m/z* 50 ~ 1 500, Production scan二级扫描范围为 *m/z* 50 ~ 1 250。

2.4 自建数据库的建立与 SCIEX 中药数据库的使用

查阅相关文献[10-34], 对脾肾两助丸中药材的化合物信息予以整理, 并构建起数据库, 其中涵盖化合物的名称、分子式以及精确相对分子质量等方面的信息。运用 SCIEX OS 2.0 软件实施峰的提取以及峰的匹配分析处理操作。在质量偏差≤5 以及同位素丰度比≤5 的前提条件下, 同文献中化合物的准分子离子峰以及碎片裂解规律展开比对分析, 最终完成化合物结构的鉴定工作。

3 结 果

3.1 辐照灭菌前后脾肾两助丸液相图谱

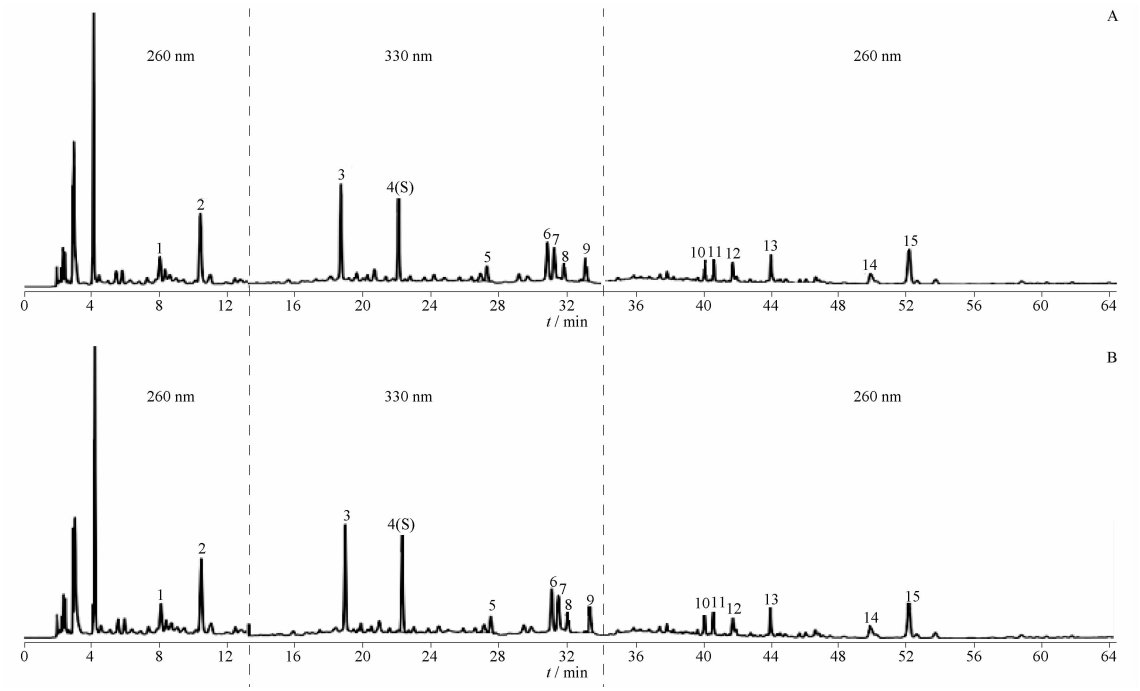
首先通过高效液相图谱对辐照前后的样品进行比较。比较 230、260、283、330 nm 4 个波长下脾肾两助丸灭菌前后的出峰面积以及分离度, 结果发现, 在 260 和 330 nm 波长下的分离度及峰形较好, 并且出峰数较多, 因此选择 260、330 nm 作为检测波长 (图 1)。在辐照灭菌前后的液相图谱中, 2 个波长下各峰的位置、相对强度以及整体图谱形态与灭菌后的图谱基本一致, 且选取 15 个峰作为特征峰计算 10 批样品灭菌前后的变化率见表 1, 15 个特征峰灭菌前后峰面积变化率均不超过 ±10%, 在可接受范围内。

3.2 脾肾两助丸的化学成分解析

采用 UHPLC-Q-TOF-MS/MS 高分辨质谱分别在正、负离子模式下采集脾肾两助丸样品质谱数据 (图 2)。通过质谱碎片解析结合标准品和文献报道数据对照, 共鉴定出 260 个化合物 (表 2), 包括 45 个黄酮类化合物, 28 个三萜类化合物, 24 个苯丙素类化合物, 以及糖苷类、有机酸类、脂类、氨基酸类、生物碱类其他类等化合物 163 个。

3.2.1 黄酮类化合物鉴定 在脾肾两助丸中共鉴定出 47 个黄酮类化合物。其中包括 24 个黄酮醇类化合物、12 个异黄酮类化合物、9 个二氢黄酮类化合物、1 个黄烷醇类化合物和 1 个查尔酮类化合物, 这些黄酮类化合物来源于黄芪、杜仲、牛膝、白芍、陈皮、川贝母、补骨脂、锁阳、山药、地黄、款冬花等中药。黄酮类化合物在裂解过程中容易失去 CO、H_2O、CO_2 等中性分子, C 环发生逆狄尔斯-阿尔德 (RDA) 裂解, 其苷元容易发生糖苷键断裂[10]。化合物 13 准分子离子峰为 *m/z* 609.146 4 $[M-H]^-$, 失去糖中性碎片 $C_{12}H_{20}O_9$ 后产生苷元碎片 *m/z* 301.035 6 $[M-H-C_{12}H_{20}O_9]^-$, 苷元碎片发生 RDA 裂解, 失去 $C_8H_6O_3$ 产生碎片离子 *m/z* 151.003 4 $[M-H-C_8H_6O_3]^-$。此外, 苷元碎片丢失 1 分子 H_2O、CO 产生碎片离子 *m/z* 255.030 0 $[M-H-C_{12}H_{20}O_9-H_2O-CO]^-$, 该碎片离子经重排后 H_2O 丢失中性分子 CO 产生 *m/z* 227.035 3 的碎片离子[11], 与标准品的质谱数据一致, 因此推断化合物 13 为芦丁。

3.2.2 三萜及其苷类化合物成分鉴定 在脾肾两助丸中共鉴定出 41 个萜类化合物, 其中包含 28 个三萜类化合物, 分别是 20 个四环三萜类化合物和 8 个五环三萜类化合物, 这些三萜类化合物来源于牛膝、泽泻、甘草、茯苓、陈皮、和白芍等中药。三萜类化合物在裂解过程中容易发生糖苷键的断裂, α-和 β-消除反应、酯键裂解。化合物 76 在正离子扫描模式下准分子离子峰为 *m/z* 823.410 7 $[M+H]^+$,



峰 1 ~ 15 为选取的 15 个特征峰。

Peaks 1 – 15 are the selected 15 characteristic peaks.

图 1 未灭菌(A)与灭菌(B)脾肾两助丸特征图谱

Fig. 1 Characteristic chromatograms of Pishenliangzhu Pills before(A) and after(B) sterilization

表 1 脾肾两助丸灭菌前后峰面积差异。$n = 10, \bar{x} \pm s$

Tab. 1 Area differences of Pishenliangzhu Pills before and after sterilization. $n = 10, \bar{x} \pm s$

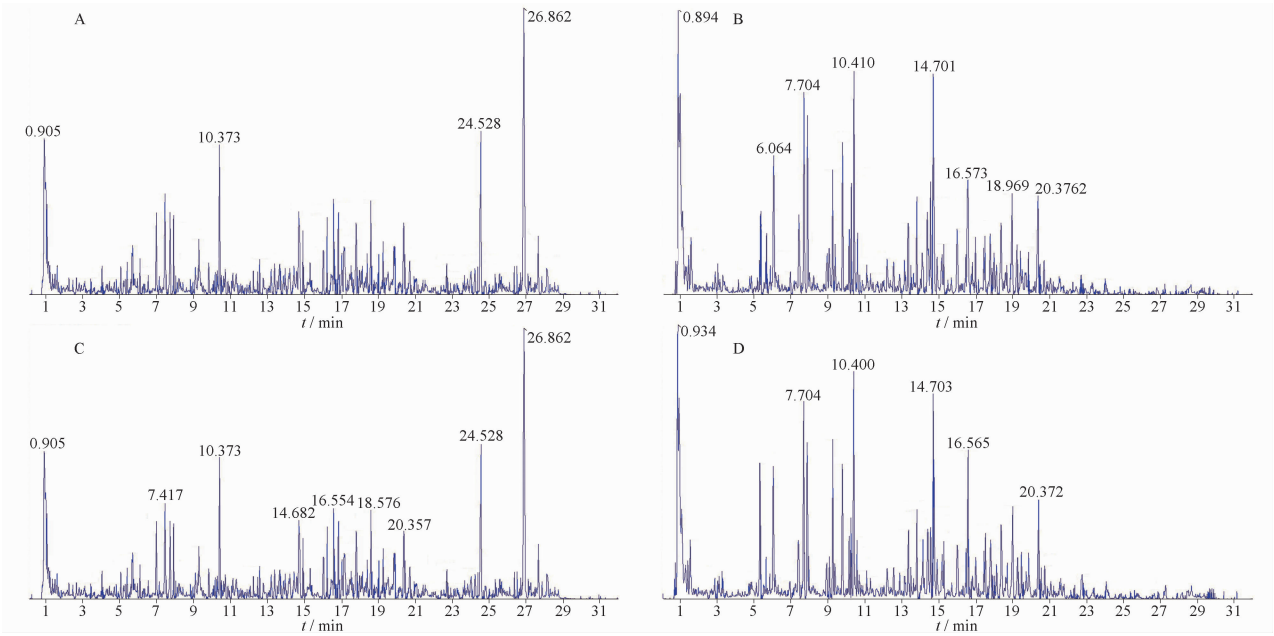
Wavelength /nm	Peak No.	$\bar{x} \pm s$		Rate of change/%
		Before sterilization	After sterilization	
260	1	180.96 ± 13.31	177.88 ± 13.35	−1.66
	2	557.35 ± 14.33	507.71 ± 12.93	−9.63
	10	94.01 ± 22.90	91.84 ± 23.14	−2.50
	11	99.36 ± 21.78	97.98 ± 22.73	−1.62
	12	104.31 ± 5.09	97.73 ± 17.7	−6.40
	13	127.99 ± 10.64	117.25 ± 8.09	−8.11
	14	124.2 ± 5.90	112.02 ± 10.36	−9.93
	15	360.08 ± 44.01	324.02 ± 39.58	−9.88
330	3	482.99 ± 23.55	458.07 ± 33.87	−5.22
	4	480.84 ± 53.92	485.17 ± 47.73	1.22
	5	124.72 ± 18.36	122.81 ± 19.28	−1.58
	6	277.28 ± 21.56	267.46 ± 25.14	−3.52
	7	259.29 ± 27.26	250.86 ± 35.88	−2.88
	8	114.89 ± 8.67	116.60 ± 7.91	1.90%
	9	153.55 ± 16.86	150.32 ± 15.85	−1.70

进一步裂解得到碎片离子 *m/z* 647.371 6[M + H − $C_6H_8O_6$]$^+$、*m/z* 471.346 4[M + H − $2C_6H_8O_6$]$^+$，失去 H_2O 得到碎片离子 *m/z* 453.325 2[M + H − $2C_6H_8O_6$ − H_2O]$^+$[13]，与标准品的质谱数据一致，因此推断化合物 76 为甘草酸。

3.2.3 苯丙素类化合物成分鉴定 在脾肾两助丸中共鉴定出 24 个苯丙素类化合物，包括 16 个简单苯丙素类化合物和 7 个香豆素类化合物，以及 1 个木脂素类化合物。这些苯丙素类化合物来源于补骨脂、杜仲、党参、白术、山药、陈皮、川贝母、牵牛子、黄芪、枸杞子、牛膝、当归、川芎等中药。苯丙素类化合物容易失去 CH_3、H_2O、CO_2 和糖基等基团。如化合物 164 准分子离子峰为 *m/z* 193.051 0[M − H]$^-$，失去 CH_3 得到碎片离子 *m/z* 178.022 5[M − H − CH_3]$^-$，失去 CO_2 产生碎片离子 *m/z* 149.059 7[M − H − CO_2]$^-$，相继丢失 CH_3 和 CO_2 产生碎片离子 *m/z* 134.035 9[M − H − CH_3 − CO_2]$^-$[15]，与标准品的质谱数据一致，因此推断化合物 164 为阿魏酸。

3.3 多元统计分析

3.3.1 主成分分析(principal component analysis，PCA)与聚类分析 将灭菌前后的 20 批脾肾两助丸原始质谱数据预处理后进行 PCA，从图 3 可以看出，所有质量控制(quality control，QC)样本落在 2SD 范围内，说明仪器运行过程中稳定良好，灭菌前后样本没有明显区分。进一步进行聚类分析(图 4)，同一批样品灭菌前后基本聚为一类，说明灭菌前后 10 批脾肾两助丸样品只存在批次间的差异，而灭菌前后无明显差异。



A – 正离子模式下灭菌前;B – 正离子模式下灭菌后;C – 负离子模式下灭菌前 D;负离子模式下灭菌后。

A – before sterilization in positive ion mode;B – after sterilization in positive ion mode;C – before sterilization in negative ion mode;D – after sterilization in negative ion mode.

图 2 正负离子模式下脾肾两助丸辐照前后总离子流对比图

Fig. 2 Total ion current comparison chart of Pishenliangzhu Pills before and after irradiation in positive and negative ion modes

表 2 脾肾两助丸已鉴定成分

Tab. 2 Identified ingredients of Pishenliangzhu Pills

No.	Identification	Molecular formula	$[M+H]^+$ /$[M-H]^-$	*m/z*	t_R /min	Error /$\times 10^{-6}$	*P*	Type
1	Formononetin	$C_{16}H_{12}O_4$	$[M-H]^-$	269.080 7	14.92	−0.6	0.467 085 89	Flavonoids
2	Naringenin	$C_{15}H_{12}O_5$	$[M-H]^-$	271.061 1	13.64	−0.5	0.184 778 644	Flavonoids
3	Astragalin	$C_{21}H_{20}O_{11}$	$[M-H]^-$	447.091 9	10.18	−3.2	0.351 439 875	Flavonoids
4	Kaempferol	$C_{15}H_{10}O_6$	$[M-H]^-$	285.040 4	13.91	−0.3	0.804 814 613	Flavonoids
5	Isoafrormosin	$C_{17}H_{14}O_5$	$[M-H]^-$	297.077 1	16.91	0	0.095 099 176	Flavonoids
6	Chrysoeriol	$C_{16}H_{12}O_6$	$[M-H]^-$	299.055 7	12.36	−1.3	0.440 965 197	Flavonoids
7	Quercetin	$C_{15}H_{10}O_7$	$[M-H]^-$	301.034 6	12.61	−2.4	0.425 528 475	Flavonoids
8	Isoorientin	$C_{21}H_{20}O_{11}$	$[M-H]^-$	447.091 9	8.04	−3.0	0.058 288 041	Flavonoids
9	Isoquercetin	$C_{21}H_{20}O_{12}$	$[M-H]^-$	463.087 8	9.32	−0.9	0.164 714 461	Flavonoids
11	Poncirin	$C_{28}H_{34}O_{14}$	$[M+H]^+$	593.177	12.21	−0.9	0.562 968 004	Flavonoids
12	Ellagic acid	$C_{14}H_6O_8$	$[M-H]^-$	300.9987	9.16	−0.9	0.372 350 78	Flavonoids
13	Eriocitrin	$C_{27}H_{32}O_{15}$	$[M+H]^+$	597.181	8.76	−0.7	0.945 768 76	Flavonoids
15	Rutin	$C_{27}H_{30}O_{16}$	$[M-H]^-$	609.146 4	8.93	0.5	0.214 185 793	Flavonoids
16	Neohesperidin	$C_{28}H_{34}O_{15}$	$[M-H]^-$	609.182	10.4	1.3	0.207 985 08	Flavonoids
17	Isomucronulatol-*O*-Glc-ACE	$C_{25}H_{30}O_{11}$	$[M-H]^-$	507.186 6	13.87	0.9	0.935 507 099	Flavonoids
18	Daidzein	$C_{15}H_{10}O_4$	$[M+H]^+$	255.065	12.04	−0.8	0.874 763 114	Flavonoids
19	Calycosin	$C_{16}H_{12}O_5$	$[M-H]^-$	285.075 7	12.57	−0.2	0.247 104 611	Flavonoids
20	Catechin	$C_{15}H_{14}O_6$	$[M+H]^+$	291.086	6.2	−0.7	0.268 000 216	Flavonoids
21	Isomucronulatol isomer	$C_{17}H_{18}O_5$	$[M-H]^-$	303.122 6	15.43	−0.4	0.357 458 137	Flavonoids
22	Epigallocatechin	$C_{15}H_{14}O_7$	$[M+H]^+$	307.081	2.11	6.1	0.479 126 244	Flavonoids
23	5-Hydroxy-6,7,8,3′,4′-pentamethoxyflavanone	$C_{20}H_{20}O_8$	$[M-H]^-$	389.122 6	18.12	−1.3	0.559 916 017	Flavonoids
24	Nobiletin	$C_{21}H_{22}O_8$	$[M+H]^+$	403.138 8	16.21	0.1	0.995 957 756	Flavonoids
25	Ononin	$C_{22}H_{22}O_9$	$[M-H]^-$	431.133 6	11.41	−0.1	0.417 510 214	Flavonoids
26	3,5,6,7,8,3′,4′-Heptemthoxyflavone	$C_{22}H_{24}O_9$	$[M+H]^+$	433.148 8	16.81	−1.3	0.468 842 223	Flavonoids
27	Baicalin	$C_{21}H_{18}O_{11}$	$[M+H]^+$	447.092	11.42	−1.1	0.663 990 813	Flavonoids
28	3-(2,3-Dihydro-1,4-benzodioxin-6-yl)-4-oxo-4*H*-chromen-7-yl hexopyranoside	$C_{23}H_{22}O_{10}$	$[M-H]^-$	459.128	10.77	−1.4	0.336 421 354	Flavonoids

续表 2(continued)

No.	Identification	Molecular formula	[M + H]$^+$ /[M − H]$^-$	*m/z*	t_R /min	Error /×10^{-6}	*P*	Type
29	Quercetin-4′-*O*-*β*-D-glucoside	$C_{21}H_{20}O_{12}$	[M + H]$^+$	465.102 3	9.32	−1.0	0.656 487 033	Flavonoids
30	Apiin	$C_{26}H_{28}O_{14}$	[M + H]$^+$	565.155	7.92	−0.3	0.972 380 612	Flavonoids
31	Procyanidin B2	$C_{30}H_{26}O_{12}$	[M + H]$^+$	579.15	5.47	0.4	0.071 805 51	Flavonoids
32	Phlorizin	$C_{21}H_{24}O_{10}$	[M − H]$^-$	435.128 7	11.03	−2.3	0.390 464 224	Flavonoids
33	Odoratin	$C_{17}H_{14}O_6$	[M − H]$^-$	315.085 9	12.82	−1.4	0.631 368 417	Flavonoids
34	Sarothamnoside	$C_{37}H_{46}O_{23}$	[M − H]$^-$	859.249 5	11.86	−0.9	0.772 638 25	Flavonoids
35	Hesperetin-7-*O*-*β*-D-glucoside	$C_{22}H_{24}O_{11}$	[M − H]$^-$	465.139 6	10.4	1.0	0.562 231 248	Flavonoids
36	Pratensein	$C_{16}H_{12}O_6$	[M − H]$^-$	301.070 5	10.57	−0.5	0.578 970 013	Flavonoids
37	Formononetin-7-*O*-Glc-6″-*O*-acetate isomer	$C_{24}H_{24}O_{10}$	[M − H]$^-$	471.130 6	12.46	−2.6	0.463 365 663	Flavonoids
38	Apigenin	$C_{15}H_{10}O_5$	[M − H]$^-$	271.059 9	13.71	−0.7	0.848 328 25	Flavonoids
39	Isosinensetin	$C_{20}H_{20}O_7$	[M − H]$^-$	373.128 1	15.31	−0.2	0.716 120 562	Flavonoids
40	Kaempferol-7-*O*-*β*-D-glucopyranoside	$C_{21}H_{20}O_{11}$	[M − H]$^-$	449.107 7	10.17	−0.4	0.962 508 996	Flavonoids
41	Narirutin	$C_{27}H_{32}O_{14}$	[M + H]$^+$	581.186 1	9.8	−0.7	0.821 204 967	Flavonoids
42	Vicenin-2	$C_{27}H_{30}O_{15}$	[M − H]$^-$	595.165 7	7.14	0.0	0.441 206 69	Flavonoids
43	Hesperidin	$C_{28}H_{34}O_{15}$	[M + H]$^+$	611.197 3	10.39	0.4	0.927 021 012	Flavonoids
44	Nobiletin	$C_{21}H_{22}O_8$	[M + H]$^+$	403.138 9	16.20	0.5	0.995 957 756	Flavonoids
45	Tangeretin	$C_{20}H_{20}O_7$	[M + H]$^+$	373.128 1	17.16	−0.2	0.747 816 228	Flavonoids
46	Liquiritin	$C_{21}H_{22}O_9$	[M − H]$^-$	417.119 3	9.09	0.4	0.498 306 726	Flavonoids
47	Phloretin-3′,5′-di-*C*-glucoside	$C_{27}H_{34}O_{15}$	[M − H]$^-$	597.182	9.21	−0.8	0.255 588 922	Flavonoids
48	Limocitrin-3-*O*-HMG-*β*-glucoside	$C_{29}H_{32}O_{17}$	[M − H]$^-$	651.157	10.78	0.6	0.328 592 322	Gycosides
49	2-*O*-*β*-D-Glucopyranosyl-L-ascorbic acid	$C_{12}H_{18}O_{11}$	[M − H]$^-$	337.077 3	1.47	−1.1	0.834 530 887	Gycosides
50	8-Debenzoylpaeoniflorin	$C_{16}H_{24}O_{10}$	[M − H]$^-$	394.171	5.29	−0.9	0.085 900 884	Gycosides
51	Protocatechuic acid-4-glucoside	$C_{13}H_{16}O_9$	[M − H]$^-$	315.072 5	3.89	1.0	0.459 093 157	Gycosides
52	1-Galloylglucose	$C_{13}H_{16}O_{10}$	[M − H]$^-$	331.067 4	2.51	1	0.490 483 666	Gycosides
53	Glucosyringic acid	$C_{15}H_{20}O_{10}$	[M − H]$^-$	359.098	4.6	−2.6	0.196 475 911	Gycosides
54	Benzyl 2-*O*-*β*-D-xylopyranosyl-*β*-D-glucopyranoside	$C_{18}H_{26}O_{10}$	[M − H]$^-$	401.145 1	6.69	−0.6	0.297 971 687	Gycosides
55	Aromadendrin-7-*O*-glucoside	$C_{21}H_{22}O_{11}$	[M − H]$^-$	449.109	7.42	−1.0	0.354 937 315	Gycosides
56	Trihydroxyl-dimethoxyisoflavan-Glc	$C_{22}H_{26}O_{10}$	[M − H]$^-$	449.145 8	7.9	1.1	0.456 311 318	Gycosides
57	Isomucronulatol-acetyl-Glc	$C_{26}H_{32}O_{13}$	[M − H]$^-$	551.175 9	12.99	−2.0	0.849 275 542	Gycosides
58	7,4-dihydroxy-5,6,8,3-tetr amethoxyflavonol-3-*O*-HMG-*β*-glucoside	$C_{31}H_{36}O_{18}$	[M + H]$^+$	695.183	12.7	5.1	0.836 104 913	Gycosides
59	Narirutin 4′-glucoside	$C_{33}H_{42}O_{19}$	[M − H]$^-$	741.224 9	7.46	0.2	0.285 367 11	Gycosides
60	Glycerol diphenolic ether 4″-*O*-*β*-D-glucopyranosider	$C_{37}H_{46}O_{16}$	[M − H]$^-$	745.269 5	11.3	−2.5	0.628 376 8	Gycosides
61	Limocitrin-3-*O*-(5-α-glucsyl-HMG)-*β*-glucoside	$C_{35}H_{42}O_{22}$	[M + H]$^+$	813.209	9.91	0.8	0.288 697 862	Gycosides
62	Monohydroxypentamethoxyflavonol-3-*O*-(5-α-glucosyl-HMG)-*β*-glucoside	$C_{38}H_{48}O_{23}$	[M + H]$^+$	871.251	11.69	−0.4	0.260 970 324	Gycosides
63	Astraisoflavan-malonyl-Glc	$C_{26}H_{30}O_{13}$	[M − H]$^-$	551.175 8	12.99	−0.1	0.121 390 767	Gycosides
64	Trihydroxy-dimethoxyisoflavan-Glc-Glc	$C_{29}H_{38}O_{16}$	[M + NH_4]$^+$	660.248 7	7.22	−1.7	0.332 092 548	Gycosides
65	Limocitrin-3-*O*-HMG-*β*-glucoside	$C_{29}H_{32}O_{17}$	[M + H]$^+$	653.170 7	10.78	−0.7	0.431 929 702	Gycosides
66	Calycosin-7-*O*-Glc	$C_{22}H_{22}O_{10}$	[M − H]$^-$	447.127 9	8.83	−1.4	0.674 106 67	Gycosides
67	Astrapterocarpan-3-*O*-Glc	$C_{23}H_{26}O_{10}$	[M − H]$^-$	463.159 6	12.02	−0.7	0.282 668 264	Gycosides
68	Isomucronulatol-7-*O*-Glc	$C_{23}H_{28}O_{10}$	[M − H]$^-$	465.175 1	12.26	−1.0	0.782 969 372	Gycosides
69	Apigenin-malonyl-Glc	$C_{24}H_{22}O_{13}$	[M − H]$^-$	519.112 8	11.13	−1.0	0.917 109 026	Gycosides
70	Natsudaidain-3-*O*-(5-α-glucosyl-HMG)-*β*-glucoside	$C_{39}H_{50}O_{23}$	[M + H]$^+$	887.281 7	12.35	0.1	0.706 611 836	Gycosides
71	Naringenin-malonyl-Glc	$C_{24}H_{24}O_{13}$	[M − H]$^-$	521.129 4	11.62	0.9	0.737 729 78	Gycosides
72	Astrapterocarpan-*O*-malonyl-Glc	$C_{26}H_{28}O_{13}$	[M − H]$^-$	549.159 4	12.78	−1.5	0.683 624 176	Gycosides
73	Monohydroxy pentamethoxyflavonol-3-*O*-HMG-*β*-glucoside	$C_{32}H_{38}O_{18}$	[M + H]$^+$	711.212 7	12.46	−0.5	0.776 085 998	Gycosides
74	Acteoside	$C_{29}H_{36}O_{15}$	[M − H]$^-$	623.198 1	9.27	−0.6	0.312 847 577	Gycosides
75	Licoricesaponin B2	$C_{42}H_{64}O_{15}$	[M + H]$^+$	809.432	15.12	0.6	0.522 916 084	Triterpenoids saponins
76	Licoricesaponin G2	$C_{42}H_{62}O_{17}$	[M + H]$^+$	839.405 8	14.15	−0.2	0.814 763 576	Triterpenoids saponins
77	24-Hydroxy-licorice-saponin A3	$C_{48}H_{72}O_{22}$	[M + H]$^+$	1 001.459	12.35	−0.4	0.443 130 119	Triterpenoids saponins
78	Glycyrrhizic acid	$C_{42}H_{62}O_{16}$	[M + H]$^+$	823.410 7	14.7	−0.4	0.680 330 305	Triterpenoids saponins
79	Achyranthoside E	$C_{46}H_{70}O_{19}$	[M − H]$^-$	925.446 5	14.77	2.8	0.275 023 552	Triterpenoids saponins
80	Achyranthoside D	$C_{53}H_{82}O_{25}$	[M − H]$^-$	1 117.506 2	13.81	−1.0	0.725 851 971	Triterpenoids saponins
81	Achyranthoside B	$C_{47}H_{70}O_{20}$	[M − H]$^-$	953.44	14.4	1.3	0.226 444 226	Triterpenoids saponins

续表 2(continued)

No.	Identification	Molecular formula	[M+H]$^+$ /[M−H]$^-$	m/z	t_R /min	Error /×10^{-6}	P	Type
82	Achyranthoside G	$C_{47}H_{72}O_{20}$	[M−H]$^-$	955.455 1	14.55	0.7	0.713 359 44	Triterpenoids saponins
83	Zingibroside R1	$C_{42}H_{66}O_{14}$	[M−H]$^-$	793.438 3	14.61	0.4	0.003 768 491	Triterpenoids saponins
84	28-Deglucosyl-achyranthoside C	$C_{41}H_{62}O_{15}$	[M−H]$^-$	793.401 6	17.89	0.1	0.500 790 838	Triterpenoids saponins
85	Achyranthoside Ⅳ	$C_{41}H_{60}O_{15}$	[M−H]$^-$	791.386 5	17.98	0.7	0.482 002 786	Triterpenoids saponins
86	28-Deglucosyl-achyranthoside E	$C_{40}H_{60}O_{14}$	[M−H]$^-$	763.390 6	18.48	−0.5	0.471 055 438	Triterpenoids saponins
87	28-Desglucosylchikusetsusaponin IVa	$C_{36}H_{56}O_9$	[M−H]$^-$	631.384 7	18.23	−0.7	0.364 016 974	Triterpenoids saponins
88	Agroastragaloside Ⅳ	$C_{49}H_{80}O_{20}$	[M−H]$^-$	987.518	15.18	0.3	0.202 412 02	Triterpenoids saponins
89	Acetylastragaloside Ⅰ	$C_{47}H_{74}O_{17}$	[M−H]$^-$	909.488 3	17.45	−2.1	0.700 812 341	Triterpenoids saponins
90	22-Hydroxy-licorice-saponin G2	$C_{42}H_{62}O_{18}$	[M+H]$^+$	855.399	12.82	−2.2	0.457 660 29	Triterpenoids saponins
91	Acetylastragaloside Ⅰ isomer	$C_{47}H_{74}O_{17}$	[M+H]$^+$	911.499 6	19.5	−0.3	0.920 484 893	Triterpenoids saponins
92	Astragaloside Ⅱ	$C_{43}H_{70}O_{15}$	[M−H]$^-$	827.476 3	15.15	−2.9	0.659 249 551	Triterpenoids saponins
93	Astragaloside Ⅳ	$C_{41}H_{68}O_{14}$	[M+H]$^+$	785.470 1	14.28	2.4	0.180 739 527	Triterpenoids saponins
94	Betulin	$C_{30}H_{50}O_2$	[M+H]$^+$	443.388	28.2	−0.7	0.289 346 918	Triterpenoids
95	Dehydrotrametenolic acid	$C_{30}H_{46}O_3$	[M+H]$^+$	455.352	24.53	−0.9	0.499 968 171	Triterpenoids
96	Limonin	$C_{26}H_{30}O_8$	[M+H]$^+$	471.207 2	15.71	−0.4	0.849 692 477	Triterpenoids
97	Alisol B	$C_{30}H_{48}O_4$	[M+H]$^+$	473.361 8	24.54	−1.6	0.414 263 797	Triterpenoids
98	Alisol B 23-acetate	$C_{32}H_{50}O_5$	[M+H]$^+$	515.372 9	26.89	−0.3	0.934 831 778	Triterpenoids
99	Pachymic acid	$C_{33}H_{52}O_5$	[M+H]$^+$	529.389	27.24	−2.1	0.838 718 934	Triterpenoids
100	Dehydrotumulosic acid	$C_{31}H_{48}O_4$	[M−H]$^-$	483.347 4	21.05	−1.3	0.417 753 099	Triterpenoids
101	Soyasaponin Ⅰ	$C_{48}H_{78}O_{18}$	[M+H]$^+$	943.525 7	15.18	−0.4	0.857 762 868	Triterpenoids
102	Alisol C monoacetate	$C_{32}H_{48}O_6$	[M+H]$^+$	529.351 9	18.62	−0.8	0.867 880 506	Triterpenoids
103	Deacetylaspe rulosidic acid	$C_{16}H_{22}O_{11}$	[M−H]$^-$	389.108 1	5.98	−2.0	0.269 451 775	Monoterpenoids
104	Geniposidic acid	$C_{16}H_{22}O_{10}$	[M−H]$^-$	373.113 5	4.17	−1.3	0.304 645 953	Monoterpenoids
105	Asperulosidic acid	$C_{18}H_{24}O_{12}$	[M−H]$^-$	431.118 6	4.09	−2.2	0.101 442 28	Monoterpenoids
106	Paeoniflorin	$C_{23}H_{28}O_{11}$	[M−H]$^-$	479.154 9	7.91	−2.1	0.323 834 32	Monoterpenoids
107	1-Deoxyeucommiol	$C_9H_{16}O_3$	[M−H]$^-$	171.102 7	12.46	0.3	0.662 489 502	Monoterpenoids
108	Curcumol	$C_{15}H_{24}O_2$	[M+H]$^+$	237.184 6	17.44	−1.3	0.774 447 926	Sesquiterpenoids
109	Tussilagone	$C_{23}H_{34}O_5$	[M+H]$^+$	391.247 7	23.89	−0.5	0.707 813 555	Sesquiterpenoids
110	Tussilagonone Ⅰ	$C_{21}H_{30}O_3$	[M+H]$^+$	331.225 9	23.89	−2.5	0.756 772 017	Sesquiterpenoids
111	Rhmannioside D	$C_{27}H_{42}O_{20}$	[M−H]$^-$	685.219 7	3.31	−0.5	0.527 295 014	Iridoid ether terpenoids
112	Loganin	$C_{17}H_{26}O_{10}$	[M−H]$^-$	435.150 1	6.98	−1.6	0.296 663 386	Iridoid ether terpenoids
113	Morroniside	$C_{17}H_{26}O_{11}$	[M−H]$^-$	451.144 9	5.68	−1.9	0.590 946 13	Iridoid ether terpenoids
114	Rehmaglutin C	$C_9H_{12}O_5$	[M−H]$^-$	199.061 2	2.45	1.8	0.516 482 859	Iridoid ether terpenoids
115	Cornuside	$C_{24}H_{30}O_{14}$	[M−H]$^-$	541.155 5	10.26	−1.4	0.354 616 954	Iridoid ether terpenoids
116	Corchorifatty acid F	$C_{18}H_{32}O_5$	[M−H]$^-$	327.217 1	13.53	−1.7	0.786 039 928	Lipids
117	Ricinoleic acid	$C_{18}H_{34}O_3$	[M−H]$^-$	297.243 3	22.04	−0.8	0.550 315 664	Lipids
118	Pinellic acid	$C_{18}H_{34}O_5$	[M−H]$^-$	329.233 2	14.12	−0.4	0.721 863 101	Lipids
119	LPE(16:0/0:0)	$C_{21}H_{44}NO_7P$	[M−H]$^-$	452.277 4	19.7	−1.9	0.721 493 382	Lipids
120	LPE(18:2/0:0)	$C_{23}H_{44}NO_7P$	[M−H]$^-$	476.277 5	18.88	−1.6	0.505 611 084	Lipids
121	LPE(18:1/0:0)	$C_{23}H_{46}NO_7P$	[M−H]$^-$	478.293 1	20.55	−1.7	0.461 280 467	Lipids
122	LPE(18:0/0:0)	$C_{23}H_{48}NO_7P$	[M−H]$^-$	480.308 6	23.27	−2.1	0.693 995 443	Lipids
123	LPG(16:0/0:0)	$C_{22}H_{45}O_9P$	[M−H]$^-$	483.271 9	22.98	−1.9	0.340 580 812	Lipids
124	LPG(18:2/0:0)	$C_{24}H_{45}O_9P$	[M−H]$^-$	507.271 3	21.36	−3.1	0.627 412 531	Lipids
125	LPS(18:2/0:0)	$C_{24}H_{44}NO_9P$	[M−H]$^-$	520.266 2	19.24	−3.7	0.898 876 786	Lipids
126	LPI(16:0/0:0)	$C_{25}H_{49}O_{12}P$	[M−H]$^-$	571.288 2	20.5	−1.2	0.206 639 203	Lipids
127	LPI(18:2/0:0)	$C_{27}H_{49}O_{12}P$	[M−H]$^-$	595.287 8	19.44	−1.8	0.532 155 138	Lipids
128	Monopalmitin	$C_{19}H_{38}O_4$	[M+H]$^+$	331.284 4	27.57	0.4	0.992 098 489	Lipids
129	1,1′-Oxybis[3-(octyloxy)propan-2-ol]	$C_{22}H_{46}O_5$	[M+NH$_4$]$^+$	408.368 3	27.95	−0.2	0.909 218 712	Lipids
130	2,3-Dihydroxypropyl(9*Z*,12*Z*)-9,12-octadecadienoate-hexose-hexose-hexose	$C_{39}H_{68}O_{19}$	[M−H]$^-$	858.468 9	17.7	−0.4	0.351 185 671	Lipids
131	Glyceryl linolenate	$C_{21}H_{36}O_4$	[M+H]$^+$	353.268 3	24.55	−0.9	0.189 936 191	Lipids
132	Gingerglycolipid B	$C_{33}H_{58}O_{14}$	[M+NH$_4$]$^+$	696.415 6	18.7	−1.2	0.423 330 161	Lipids
133	2,3-Dihydroxypropyl 9,12-octadecadienoate	$C_{21}H_{38}O_4$	[M+H]$^+$	355.284	26.34	−0.8	0.964 546 464	Lipids
136	LPC(16:2/0:0)	$C_{24}H_{48}NO_7P$	[M+H]$^+$	494.323 2	18.22	−1.8	0.721 956 281	Lipids
137	LPC(16:1/0:0)	$C_{24}H_{50}NO_7P$	[M+H]$^+$	496.339 8	19.84	0	0.766 730 442	Lipids
138	LPC(18:3/0:0)	$C_{26}H_{48}NO_7P$	[M+H]$^+$	518.323 6	17.93	−0.9	0.424 065 534	Lipids

续表 2(continued)

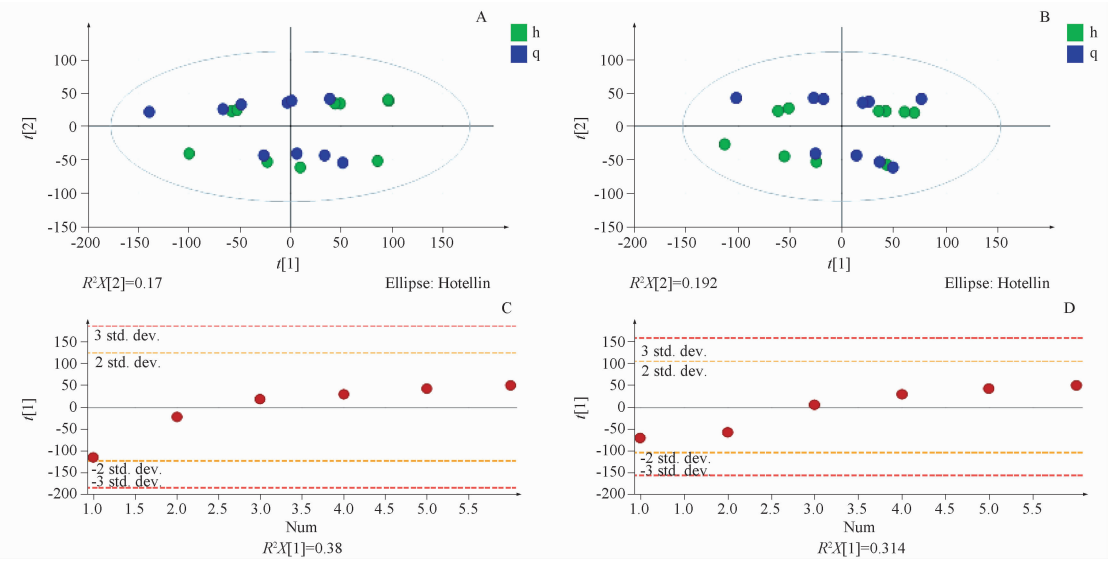
No.	Identification	Molecular formula	[M + H]$^+$ /[M − H]$^-$	m/z	t_R /min	Error /$\times 10^{-6}$	P	Type
139	LPC(18:1/0:0)	$C_{26}H_{52}NO_7P$	[M + H]$^+$	522.355 1	20.72	−0.5	0.872 106 877	Lipids
140	LPC(18:0/0:0)	$C_{26}H_{54}NO_7P$	[M + H]$^+$	524.370 1	23.52	−1.8	0.459 927 006	Lipids
141	Palmitic acid	$C_{16}H_{32}O_2$	[M − H]$^-$	255.232 9	23.34	−0.3	0.887 594 43	Lipids
142	Gingerglycolipid B	$C_{34}H_{60}O_{16}$	[M − H]$^-$	723.382	18.69	−2.6	0.501 518 02	Lipids
143	LPC(18:2/0:0)	$C_{26}H_{50}NO_7P$	[M − H]$^-$	520.339 6	18.99	−0.4	0.257 398 697	Lipids
144	Fumaric acid	$C_4H_4O_4$	[M − H]$^-$	115.003 9	1.05	7.6	0.120 860 274	Organic acids
145	L-Malic acid	$C_4H_6O_5$	[M − H]$^-$	133.015 3	1.05	8.1	0.019 400 806	Organic acids
146	Citric acid	$C_6H_8O_7$	[M + H]$^+$	191.020 4	1.65	3.6	0.027 185 801	Organic acids
147	2-Hydroxyhexadecanoic acid	$C_{16}H_{32}O_3$	[M − H]$^-$	271.227 8	26.19	−0.2	0.224 741 182	Organic acids
148	Linoelaidic acid	$C_{18}H_{32}O_2$	[M − H]$^-$	279.233	27.84	0.3	0.764 175 486	Organic acids
149	9-Hydroxy-10,12-octadecadienoic acid	$C_{18}H_{32}O_3$	[M − H]$^-$	295.228 1	20.72	0.8	0.133 142 847	Organic acids
150	(5*Z*,8*Z*,11*Z*,14*Z*)-Eicosatetraenoic acid	$C_{20}H_{32}O_2$	[M − H]$^-$	303.232 5	27.62	−1.5	0.625 469 044	Organic acids
151	13-Hpode	$C_{18}H_{32}O_4$	[M − H]$^-$	311.222 7	16.88	−0.2	0.930 670 872	Organic acids
152	(12*Z*)-9,10-Dihydroxyoctadec-12-enoic acid	$C_{18}H_{34}O_4$	[M − H]$^-$	313.238 3	17.96	−0.6	0.583 111 717	Organic acids
153	4-Pyranoxy-3-benzoic acid	$C_{14}H_{18}O_9$	[M − H]$^-$	329.087 6	4.09	−0.5	0.207 596 588	Organic acids
154	Azelaic acid	$C_9H_{16}O_4$	[M − H]$^-$	187.097 6	10.66	2.5	0.111 505 24	Organic acids
155	2-Phenylbutyric acid	$C_{10}H_{12}O_2$	[M + H]$^+$	165.091	8.59	0.1	0.009 335 515	Organic acids
156	(9*Z*,11*Z*,13*E*,15*E*)-octadecatetraenoic acid	$C_{18}H_{28}O_2$	[M + H]$^+$	277.216	21.38	−0.6	0.697 153 091	Organic acids
157	Vaccenic acid	$C_{18}H_{34}O_2$	[M + H]$^+$	283.262 8	26.59	−1.2	0.811 806 566	Organic acids
158	α-Dimorphecolic acid	$C_{18}H_{32}O_3$	[M + H]$^+$	297.242 2	23.68	−0.7	0.322 615 621	Organic acids
159	9-Hpode	$C_{18}H_{32}O_4$	[M + H]$^+$	313.236 8	16.87	−1.6	0.291 599 119	Organic acids
160	(Dimethyl N-(tert-butoxycarbonyl)-L-glutamate [(ethoxyacetyl)amino]-3-methyl-5-oxopentanoic acid	$C_{12}H_{21}NO_6$	[M − H]$^-$	276.144 2	2.31	0	0.951 189 071	Organic acids
161	3β,16α-Dihydroxylanosta-7,9(11),24-trien-21-oic acid	$C_{30}H_{46}O_4$	[M + H]$^+$	471.347	14.72	−0.4	0.979 312 061	Organic acids
162	2-Hydroxyheptanedioic acid	$C_7H_{12}O_5$	[M − H]$^-$	175.061 3	5.65	0.5	0.343 126 628	Organic acids
163	8-Acetylharpagide	$C_{17}H_{26}O_{11}$	[M − H]$^-$	405.139 3	5.7	−2.4	0.472 017 347	Phenylpropanoids
164	3,4-Dihydroxyhydrocinnamic acid	$C_9H_{10}O_4$	[M − H]$^-$	181.050 8	5.13	0.8	0.548 886 902	Phenylpropanoids
165	Cistantubuloside C1	$C_{35}H_{46}O_{21}$	[M − H]$^-$	801.248 1	6.72	2.8	0.013 884 882	Phenylpropanoids
166	4-*O*-β-Glucopyranosyl-*cis*-coumaric acid	$C_{15}H_{18}O_8$	[M − H]$^-$	325.092 7	6.12	−0.7	0.911 876 564	Phenylpropanoids
167	Dihydroferulic acid	$C_{10}H_{12}O_4$	[M − H]$^-$	195.065 8	8.6	−2.3	0.020 265 259	Phenylpropanoids
168	Ferulic acid	$C_{10}H_{10}O_4$	[M − H]$^-$	193.051	16.32	1.7	0.400 994 353	Phenylpropanoids
169	Ethyl 3-(3,4-dihydroxyphenyl)acrylate	$C_{11}H_{12}O_4$	[M − H]$^-$	207.066 3	7.26	0.3	0.029 717 781	Phenylpropanoids
170	Neochlorogenic acid	$C_{16}H_{18}O_9$	[M − H]$^-$	353.087 8	6.08	−0.1	0.513 867 144	Phenylpropanoids
171	Cistanoside F	$C_{21}H_{28}O_{13}$	[M − H]$^-$	487.145	5.28	−1.6	0.070 381 801	Phenylpropanoids
172	Isochlorogenic acid A	$C_{25}H_{24}O_{12}$	[M − H]$^-$	515.119 8	9.82	0.5	0.333 363 53	Phenylpropanoids
173	Kankanose	$C_{27}H_{38}O_{18}$	[M − H]$^-$	649.198 6	4.71	0.1	0.006 940 804	Phenylpropanoids
174	Tangshenoside Ⅰ	$C_{29}H_{42}O_{18}$	[M − H]$^-$	677.232 6	7.86	4	0.577 202 44	Phenylpropanoids
175	Nomilin glucoside	$C_{34}H_{46}O_{15}$	[M − H]$^-$	693.276	11.15	0	0.627 140 342	Phenylpropanoids
176	Echinacoside	$C_{35}H_{46}O_{20}$	[M − H]$^-$	785.250 9	7.72	−0.1	0.258 817 703	Phenylpropanoids
177	Tubuloside A	$C_{37}H_{48}O_{21}$	[M − H]$^-$	827.262 7	9.05	1.4	0.511 030 677	Phenylpropanoids
178	Chlorogenic acid	$C_{16}H_{18}O_9$	[M + H]$^-$	355.102 1	6.07	−0.6	0.373 974 476	Phenylpropanoids
179	Butylidenephthalide	$C_{12}H_{12}O_2$	[M + H]$^+$	189.091	18.7	−0.5	0.152 153 509	Phenylpropanoids
180	Corylidin	$C_{20}H_{16}O_7$	[M − H]$^-$	369.096 8	12.87	−0.1	0.589 375 972	Phenylpropanoids
181	Coumarin	$C_9H_6O_2$	[M + H]$^+$	147.043 9	10.62	−1	0.962 233 706	Phenylpropanoids
182	Formononetin-7-*O*-Glc-6″-*O*-malonate	$C_{25}H_{24}O_{12}$	[M − H]$^-$	517.133 8	12.44	−0.5	0.904 608 249	Phenylpropanoids
183	Psoralen	$C_{11}H_6O_3$	[M + H]$^+$	187.039 0,	13.66	0.1	0.769 122 625	Coumarins
184	Pinoresinol diglucoside	$C_{32}H_{42}O_{16}$	M + HCOO −	727.245	7.53	0.6	0.426 857 99	Lignans
185	Hexadecanamide	$C_{16}H_{33}NO$	[M + H]$^+$	256.263 3	26.87	−0.8	0.729 383 707	Amides
186	Oleamide	$C_{18}H_{35}NO$	[M + H]$^+$	282.279 2	27.5	0.3	0.524 719 555	Amides
187	Stearamide	$C_{18}H_{37}NO$	[M + H]$^+$	284.295 1	25.18	0.9	0.840 967 546	Amides
188	Feruloyltyramine	$C_{18}H_{19}NO_4$	[M − H]$^-$	314.138 5	11.98	−0.7	0.493 537 091	Amides
189	Citrusin Ⅲ	$C_{36}H_{53}N_7O_9$	[M + H]$^+$	728.396 6	12.76	−1.6	0.547 924 722	Alkaloids
190	Pipecolate	$C_6H_{11}NO_2$	[M − H]$^-$	130.086 8	1.01	4.4	0.819 882 466	Alkaloids
191	Stachydrine	$C_7H_{13}NO_2$	[M + H]$^+$	144.102 1	1	1.4	0.210 898 888	Alkaloids

续表 2(continued)

No.	Identification	Molecular formula	[M + H]$^+$ /[M − H]$^-$	*m/z*	t_R /min	Error /×10^{-6}	*P*	Type
192	1*H*-Indole-3-carboxaldehyde	C_9H_7NO	[M + H]$^+$	146.06	5.04	0.4	0.788 472 134	Alkaloids
193	1-[(2*R*,3*R*,4*S*,5*R*)-3,4-dihydroxy-5-(2-hydroxyethenyl)oxolan-2-yl]pyridin-1-ium-3-carboxamide	$C_{12}H_{15}N_2O_5$	[M + H]$^+$	268.104 3	2.45	−4.1	0.967 668 817	Alkaloids
194	Codonopsine	$C_{14}H_{21}NO_4$	[M + H]$^+$	268.154	4.03	0.1	0.967 668 817	Alkaloids
195	Palmitoylethanolamide	$C_{18}H_{37}NO_2$	[M + H]$^+$	300.289 5	25.48	−0.7	0.900 316 22	Alkaloids
196	α-Linolenoylethanolamide	$C_{20}H_{35}NO_2$	[M + H]$^+$	322.273 8	21.71	−0.7	0.972 763 349	Alkaloids
197	1,4-Anhydro-1-[5-carbamoyl-1-(4-nitrophenyl)-1*H*-pyrazol-3-yl]pentitol	$C_{15}H_{16}N_4O_7$	[M − H]$^-$	365.105 6	1.13	−9.8	0.801 497 626	Alkaloids
198	Synephrine	$C_9H_{13}NO_2$	[M + H]$^+$	168.101 6	1.54	−2	0.082 643 924	Alkaloids
199	5-(Ethoxycarbonyl)-2,4-dimethyl-1H-pyrrole-3-carboxylic acid	$C_{10}H_{13}NO_4$	[M − H]$^-$	210.077 6	6.92	1.9	0.586 983 694	Alkaloids
200	Betaine	$C_5H_{11}NO_2$	[M + H]$^+$	118.087 2	0.93	7.1	0.427 637 976	Alkaloids
201	Trigonelline	$C_7H_7NO_2$	[M − H]$^-$	138.055 2	0.97	1.7	0.583 310 325	Alkaloids
202	*N*-(benzylidene) methylamine	C_8H_9N	[M + H]$^+$	120.081 6	3.43	6.5	0.885 747 864	Amines
203	3-Hydroxypropyl palmitate Glc-glucosamine	$C_{31}H_{61}O_{14}N$	[M + H]$^+$	672.416 3	19.5	−0.2	0.679 209 053	Amines
204	2,2′-(Tetradecylimino) diethanol	$C_{18}H_{39}NO_2$	[M − H]$^-$	302.304 8	17.07	−1.9	0.251 742 154	Amines
205	Lauryldiethanolamine	$C_{16}H_{13}N_5O_4$	[M − H]$^-$	274.273 9	15.39	−0.5	0.146 082 422	Amines
206	Hesperitin	$C_{16}H_{14}O_6$	[M − H]$^-$	303.086	10.42	−1	0.458 197 7	Phenols
207	Catechol	$C_6H_6O_2$	[M − H]$^-$	109.030 5	5.54	9.2	0.196 752 914	Phenols
208	Pyrogallol	$C_6H_6O_3$	[M − H]$^-$	125.025	2.93	4.6	0.964 650 377	Phenols
209	Salicylic acid	$C_7H_6O_3$	[M − H]$^-$	137.024 8	5.66	2.9	0.001 327 028	Phenols
210	Coumaric acid	$C_9H_8O_3$	[M − H]$^-$	163.040 4	8.48	3.1	0.658 657 199	Phenols
211	Gallic acid	$C_7H_6O_5$	[M − H]$^-$	169.015 1	2.93	4.8	0.600 680 67	Phenols
212	Fructose	$C_6H_{12}O_6$	[M − H]$^-$	179.056	0.93	2.1	0.014 045 551	Carbohydrates
213	Sucrose	$C_{12}H_{22}O_{11}$	[M + NH_4]$^+$	360.15	1.08	−0.3	0.140 826 023	Carbohydrates
214	Melezitose	$C_{18}H_{32}O_{16}$	[M − H]$^-$	527.158	0.89	−0.4	0.738 797 797	Carbohydrates
215	Isoleucine	$C_6H_{13}NO_2$	[M + H]$^+$	132.102	2.26	4	0.095 074 537	Amino acids
216	Pantothenate	$C_9H_{17}NO_5$	[M + H]$^+$	220.118	3.86	−1.3	0.503 469 07	Amino acids
217	Proline	$C_5H_9NO_2$	[M − H]$^-$	116.0717	0.98	9.4	0.353 104 182	Amino acids
218	Arginine	$C_6H_{14}N_4O_2$	[M − H]$^-$	175.118 9	0.89	−0.2	0.115 780 865	Amino acids
219	(*S*)-2-[(tert-Butoxycarbonyl)amino]-5-methoxy-5-oxopentanoic acid	$C_{11}H_{19}NO_6$	[M − H]$^-$	262.128 3	1.02	−0.9	0.864 101 883	Amino acids
221	*N*-[(Dodecyloxy) carbonyl] valine	$C_{18}H_{35}NO_4$	[M + H]$^+$	330.263 8	16.73	−0.1	0.260 940 661	Amino acids
222	Phenylalanine	$C_9H_{11}NO_2$	[M + H]$^+$	164.072 3	3.41	3.6	0.855 272 645	Amino acids
223	Tyrosine	$C_9H_{11}NO_3$	[M − H]$^-$	180.067	2.23	2	0.996 878 993	Amino acids
224	Tryptophan	$C_{11}H_{12}N_2O_2$	[M − H]$^-$	203.082 8	5.02	1.2	0.807 044 865	Amino acids
225	*N*-Acetyl-L-phenylalanine	$C_{11}H_{13}NO_3$	[M − H]$^-$	206.082	8.32	1.3	0.266 300 695	Amino acids
226	Guanosine	$C_{10}H_{13}N_5O_5$	[M − H]$^-$	284.099	2.69	0.2	0.229 296 796	Nucleotides
227	Uridine	$C_9H_{12}N_2O_6$	[M − H]$^-$	243.062 5	2.11	0.8	0.509 658 483	Nucleotides
228	Menthyl salicylate	$C_{17}H_{24}O_3$	[M − H]$^-$	277.179 8	23.9	−0.2	0.923 646 32	Esters
229	Senkyunolide F	$C_{12}H_{14}O_3$	[M − H]$^-$	207.101 5	11.11	−0.3	0.383 971 144	Esters
230	Senkyunolide K	$C_{12}H_{16}O_3$	[M − H]$^-$	209.116 8	9.86	−2.1	0.322 799 674	Esters
231	Senkyunolide I	$C_{12}H_{16}O_4$	[M − H]$^-$	225.111 5	19.45	−2.9	0.680 484 318	Esters
232	Senkyunolide B	$C_{12}H_{12}O_3$	[M − H]$^-$	203.071 4	16.01	0.2	0.259 792 506	Esters
233	(*E*)-Ligustilide	$C_{12}H_{14}O_2$	[M + H]$^+$	191.107	18.59	1.5	0.352 615 811	Esters
234	Senkyunolide D	$C_{12}H_{14}O_4$	[M − H]$^-$	221.082	15.47	0.5	0.401 760 134	Esters
235	Phosphatidylethanolamine	$C_{23}H_{46}NO_7P$	[M − H]$^-$	480.308 5	20.55	0.1	0.210 561 275	Esters
236	Di-*n*-butyl phthalate	$C_{16}H_{22}O_4$	[M − H]$^-$	279.159	23.41,	−0.4	6.954 59E-06	Esters
237	(*E*)-β-Farnesene	$C_{15}H_{24}$	[M + H]$^+$	205.194 9	22.22	−0.9	0.095 843 292	Other categories
238	Hydroxymethylfurfural	$C_6H_6O_3$	[M + H]$^+$	127.039 6	3.65	5.1	0.195 916 46	Other categories
239	Phthalic anhydride	$C_8H_4O_3$	[M + H]$^+$	149.023 7	23.42	2.5	6.549 21E-07	Other categories
240	3-Methoxy-4-hydroxystyrene	$C_9H_{10}O_2$	[M + H]$^+$	151.075	7.9	−0.8	0.609 326 278	Other categories
241	Senkyunolide A	$C_{12}H_{16}O_2$	[M + H]$^+$	193.122	17.15	−0.3	0.067 823 511	Other categories
242	Atractylenolide Ⅵ	$C_{15}H_{22}$	[M + H]$^+$	203.179 2	21.35	−1	0.690 528 944	Other categories
243	Senkyunolide J	$C_{12}H_{18}O_4$	[M + H]$^+$	227.128	9.86	−0.9	0.782 042 616	Other categories
244	Astrapterocarpan	$C_{17}H_{16}O_5$	[M − H]$^-$	301.107 2	15.26	0.4	0.555 449 486	Other categories
245	3,6,9,12,15,18,21-Heptaoxapentatriacontan-1-ol	$C_{28}H_{58}O_8$	[M − H]$^-$	540.446 6	27.7	−0.8	0.634 627 555	Other categories

续表 2(continued)

No.	Identification	Molecular formula	[M+H]⁺ /[M−H]⁻	*m/z*	t_R /min	Error /×10⁻⁶	*P*	Type
246	Methanol caprylate caproate valerate	$C_{20}H_{36}O_7$	[M+H]⁺	389.254 9	12.95	3.8	0.576 738 853	Other categories
247	Gingerglycolipid A	$C_{33}H_{56}O_{14}$	[M−H]⁻	694.400 2	17.7	−1	0.272 901 678	Other categories
248	1-Eicosapentaenoyl-sn-glycerol-3-phosphocholine	$C_{28}H_{48}NO_7P$	[M−H]⁻	542.321 5	18.99	−4.8	0.851 396 593	Other categories
249	Pentaethylene glycol tetradecyl ether	$C_{24}H_{50}O_6$	[M+NH₄]⁺	452.394 3	27.88	−0.7	0.179 052 968	Other categories
250	Hexaethylene glycol monododecyl ether	$C_{24}H_{50}O_7$	[M+NH₄]⁺	468.388 8	24.59	−1.5	0.025 895 825	Other categories
251	Calycosin-7-*O*-Glc-6″-*O*-acetate	$C_{24}H_{24}O_{11}$	[M−H]⁻	489.138 9	11.34	−0.4	0.456 767 434	Other categories
252	Hexapolyethylene glycol monotetradecyl ether	$C_{26}H_{54}O_7$	[M+NH₄]⁺	496.420 9	27.79	0.2	0.382 021 212	Other categories
253	3,6,9,12,15,18,21-Heptaoxatritriacontan-1-ol	$C_{26}H_{54}O_8$	[M+NH₄]⁺	512.415 3	24.46	−0.8	0.002 610 917	Other categories
254	2,3-Dihydroxypropyl(9*Z*,12*Z*)-9,12-octadecadienoate-hexose	$C_{27}H_{48}O_9$	[M+NH₄]⁺	534.363 2	21.05	−0.8	0.287 177 325	Other categories
255	1-Arachidonoyl-sn-glycero-3-phosphocholine	$C_{28}H_{50}NO_7P$	[M+H]⁺	544.377 1	20.72	−5	0.507 860 811	Other categories
256	Dodecyloctaethyleneglycol monoether	$C_{28}H_{58}O_9$	[M+NH₄]⁺	556.44 11	24.35	−1.5	0.001 678 312	Other categories
257	Gingerglycolipid C	$C_{33}H_{60}O_{14}$	[M+H]⁺	698.431 5	20.27	−0.8	0.692 878 042	Other categories
258	1-[(2*S*,3*R*)-3-decoxy-1-[1-(1,3-dihydroxybutan-2-yloxy)-2,2-dihydroxyethoxy]-6-[3,4,5-trihydroxy-6-(hydroxymethyl)oxan-2-yl]oxyhexan-2-yl]oxy-4-methoxypentane-1,2,3,5-tetrol	$C_{34}H_{68}O_{19}$	[M+H]⁺	781.441 1	26.67	−2.1	0.708 163 533	Other categories
259	22*β*-Acetoxyglycyrrhizin	$C_{44}H_{64}O_{18}$	[M+H]⁺	881.416 3	13.37	−0.3	0.619 314 079	Other categories
260	20-Hydroxyecdysone	$C_{27}H_{44}O_7$	[M+HCOO]⁻	525.306 9	9.07	−1.6	0.555 653 838	Other categories
261	Angelicin	$C_{11}H_6O_3$	[M+H]⁺	187.038 8	13.95	−0.7	0.851 842 958	Coumarins
262	Sipeimine	$C_{27}H_{43}NO_3$	[M+H]⁺	430.332	9.65	0.2	0.648 147 373	Alkaloids
263	Ruscogenin	$C_{27}H_{42}O_4$	[M+H]⁺	431.316	17.68	−0.1	0.959 568 05	Other categories
264	Umbelliferone	$C_9H_6O_3$	[M+H]⁺	163.039 1	6.06	0.8	0.931 609 371	Coumarins
265	Atractylenolide Ⅲ	$C_{15}H_{20}O_3$	[M+H]⁺	249.148 3	17.01	−1.1	0.138 611 166	Sesquiterpenoids



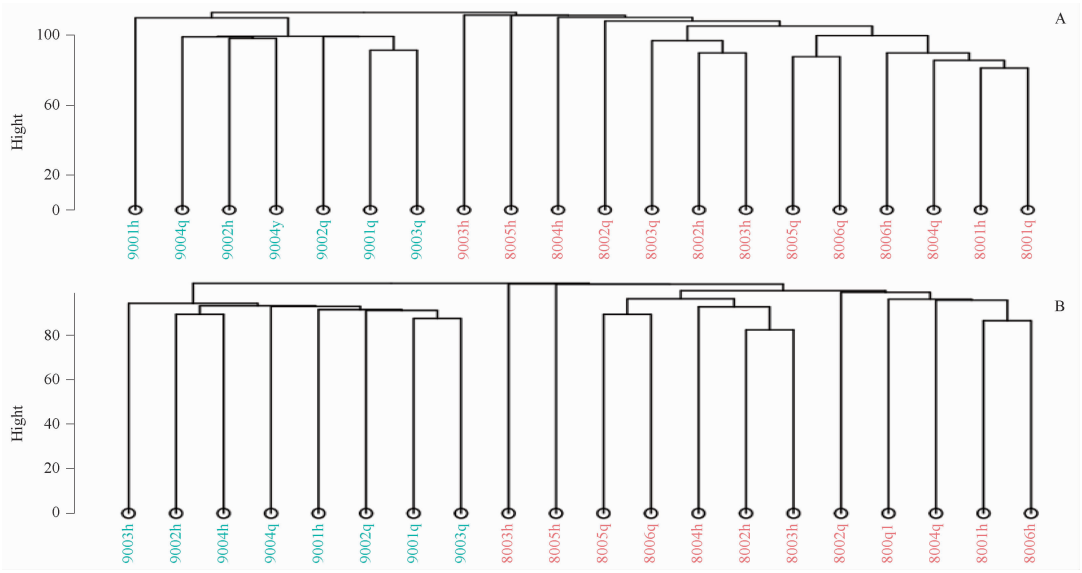
A,C − 负离子模式;B,D − 正离子模式;q − 灭菌前;h − 灭菌后。

A,C − negative ; B,D − positive; q − Before sterilization; h − After sterilization.

图 3 脾肾两助丸灭菌前后无监督主成分分析(PCA)及质控样本分布图

Fig. 3 Unsupervised PCA analysis and QC sample distribution plots of Pishenliangzhu Pills before and after sterilization

3.3.2 化学成分差异分析 首先针对《中国药典》2020 年版所规定的单味药的指标成分进行比较,在脾肾两助丸处方所含的 30 味中药里,15 味中药具有明确的含量测定指标,即黄芪、陈皮、白芍、杜仲、川贝母、款冬花、肉苁蓉、甘草、泽泻、地黄、补骨脂、当归、牛膝、枸杞子、麦冬,涉及 22 个指标成分。灭菌后 22 个指标成分中仅有甜菜碱含量明显降低(P = 0.042 763 798),变化率为(0.931 3 ± 0.308 0),见图 5。在质谱鉴定的其余 243 个成分中,有 12 个化学成分存在显著差异。因此,在质谱鉴定的 260 个成分中,共有 13 个化学成分在灭菌后有明显变化,通过 FC 值(FC = 灭菌后/灭菌前)表示各成分



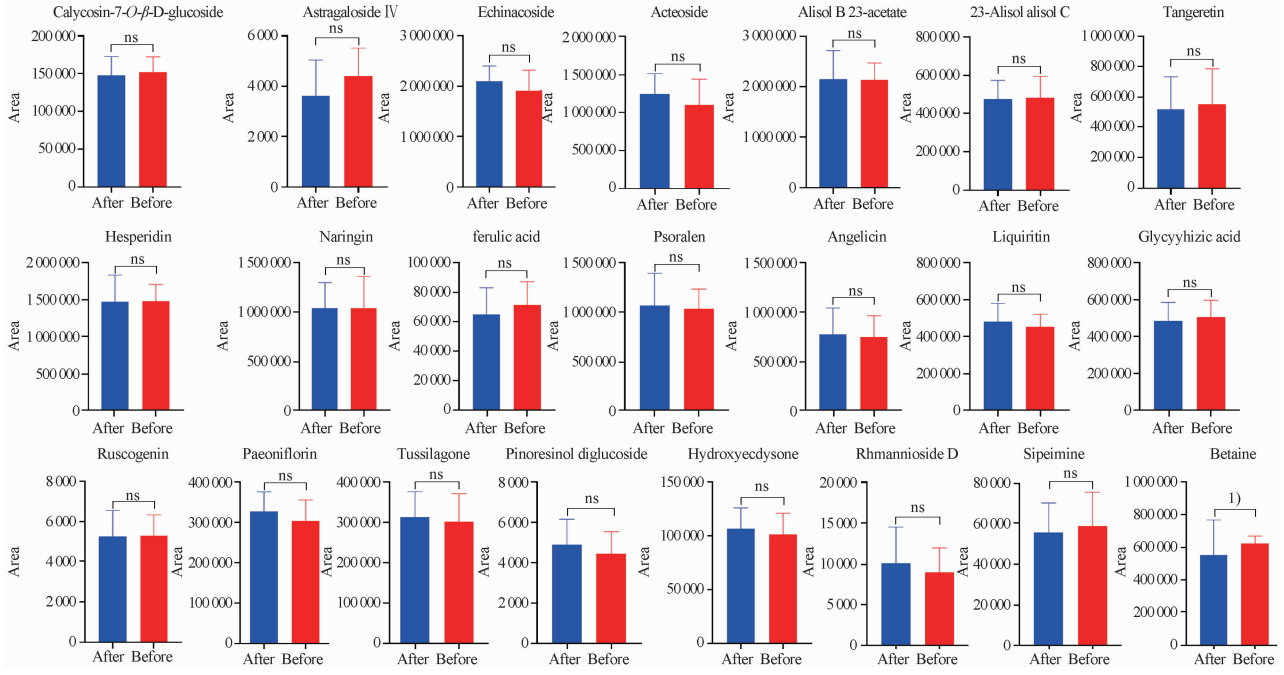
A – 负离子模式;B – 正离子模式;q – 灭菌前;h – 灭菌后。

A – negative; B – positive; q – Before sterilization; h – After sterilization.

图 4 脾肾两助丸灭菌前后聚类分析图

Fig. 4 Cluster analysis plots of Pishenliangzhu Pills before and after sterilization

灭菌前后的变化率(表 1)。13 个化学成分中,10 个成分的 FC 值在 0.8 ~ 1.3 之间。此外,这些成分的变化率与代谢组学分析的相对标准偏差(RSD)相当。



与灭菌前相比,ns – $P > 0.05$,无显著性差异,[1] $P < 0.05$,具有显著性差异。

ns – $P > 0.05$, no significant difference, [1] $P < 0.05$, significant difference, compared with before sterilization.

图 5 脾肾两助丸中中药指标性成分灭菌前后差异。$n = 10$, $\bar{x} \pm s$

Fig. 5 Differences in key traditional Chinese medicine components of Pishenliangzhu Pills before and after sterilization. $n = 10$, $\bar{x} \pm s$

13 个成分中,L-苹果酸,D-果糖,柠檬酸为初生代谢产物,在许多生物的代谢过程中都起着重要的作用。水杨酸是一种植物激素参与种子萌发、生长调节、开花诱导、产热,特别是生物或非生物胁迫

表 3 脾肾两助丸中 13 个成分灭菌前后 P 值与 Fc 值。$n=10, \bar{x} \pm s$

Tab. 3 P-values and fold change (Fc) of 13 components in Pishenliangzhu Pills before and after sterilization. $n=10, \bar{x} \pm s$

No.	Compound	P value	Fc value
1	Ethyl 3-(3,4-dihydroxy phenyl) acrylate	0.029 717 781	1.36 ± 0.46
2	Dihydroferulic acid	0.020 265 259	1.23 ± 0.32
3	L-Malic acid	0.019 400 806	1.14 ± 0.17
4	Kankanose	0.006 940 804	1.30 ± 0.33
5	Salicylic acid	0.001 327 028	1.53 ± 0.28
6	Zingibroside R1	0.003 768 491	1.57 ± 0.29
7	D-Fructose	0.014 045 551	1.13 ± 0.16
8	Dodecylheptaglycol	0.002 610 917	0.81 ± 0.13
9	Lauryl hexaethoxylate	0.025 895 825	0.89 ± 0.12
10	Dodecyloctaethyleneglycol ether	0.001 678 312	0.90 ± 0.09
11	Citric acid	0.027 185 801	1.11 ± 0.14
12	Cistantubuloside C1	0.013 884 882	1.27 ± 0.34
13	Betaine	00.042 763 798	0.93 ± 0.30

条件下植物反应的调节,可能参与不同的信号转导过程[35],与药材功效相关性不大。

二氢阿魏酸存在于枸杞子、款冬花、党参等多种植物中,具有抗氧化,清除自由基的活性[36]。甜菜碱存在于枸杞子、牛膝、肉苁蓉和锁阳等植物中,是一种常用的营养补充剂,在渗透调节以及甲基代谢当中起着关键作用,具有抗氧化、保护肝脏、调节脂质代谢以及神经保护等多种生物活性[37]。这两种成分在灭菌后虽然有显著变化,但广泛存在于多种药材中,并非药材的特征性成分,与脾肾两助丸功效相关性不大。

Ethyl 3-(3,4-dihydroxyphenyl)acrylate 存在于杜仲和牵牛子中,具有抗炎作用[38];姜状三七苷 R1 存在于牛膝中,具有抗肿瘤和抗血管生成活性,以及 HIV-1 抑制作用[39]。Dodecylheptaglycol, Lauryl hexaethoxylate,dodecyloctaethyleneglycol ether 存在于半夏中,未见活性报道。在半夏鉴定的 33 个成分中,发生变化的成分有 3 个,发生变化的占比为 9.0%。kankanose, cistantubuloside C1 是肉苁蓉的特有成分,kankanose 具有血管松弛活性[40],cistantubuloside C1 具有抗氧化活性[41]。在肉苁蓉鉴定的 12 个化学成分中,其中发生变化的成分有 2 个,发生变化的占比为 16%。根据本研究结果,辐照灭菌可能对肉苁蓉中 kankanose、cistantubuloside C1 有一定的影响,但是还需进一步的含量测定来确证。

综上,高分辨质谱代谢组学的结果提示,辐照灭菌后脾肾两助丸的整体化学成分并未产生明显变化。

4 结 论

辐照灭菌在中药及其制剂领域有广泛应用,是中药制药领域中常见的灭菌方法。尽管已有研究采用液相含测或指纹图谱等方法分析辐照灭菌对中药化学组成的影响,但难以全面反映辐照灭菌前后中药化学复杂物质组成的变化。UHPLC-Q-TOF-MS 作为一种现代分析技术,因其高灵敏度、高分辨率和高选择性而被广泛用于中草药中非靶标化合物和痕量代谢物的鉴定及分析,可实现复杂样品的快速分离和多组分的准确定性分析。本研究借助 UHPLC-Q-TOF-MS 技术全面探究了脾肾两助丸在钴-60 辐照灭菌前后的化学差异。通过高分辨质谱共鉴定出 260 个化合物,包括黄酮类、三萜类、苯丙素类等多种类型。多元统计分析提示脾肾两助丸的大部分成分在钴-60 辐照灭菌前后并未见明显变化。进一步与对鉴定的化学成分进行比较,仅有 13 个成分在灭菌前后呈现出差异,说明钴-60 辐照灭菌对脾肾两助丸整体化学组成影响不大。本研究以脾肾两助丸为例,证明了高分辨质谱在中药辐照灭菌化学研究中的应用前景,也为辐照灭菌技术在中成药生产中的应用提供了科学依据。

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(收稿日期:2024-09-05)