

第二届全国核电子学与核探测技术学术年会

自准直SPECT成像技术

马天予

清华大学工程物理系 长聘副教授

IEEE Transactions on Medical Imaging 期刊编委

中国核学会核医学分会 常务理事

2022.11.10

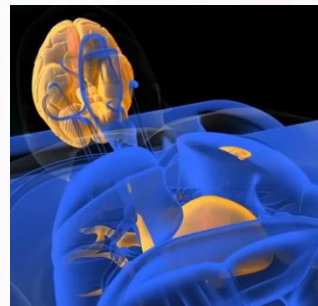


清华大学
Tsinghua University

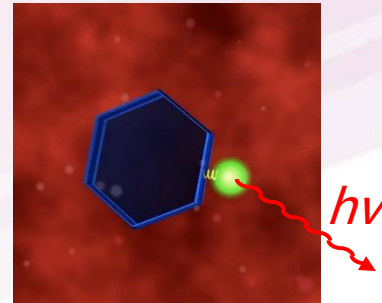
- 单光子发射断层成像 (SPECT)
 - 核素标记 + 靶向示踪 + 辐射探测 + 三维重建
- 全球人体SPECT装机 > 20000台¹
 - 用于肿瘤转移/心脑血管/内分泌/肝/肾/肺疾病诊断
- 全球小动物SPECT装机 ~ 1500台²
 - 用于临床/临床前基础研究; 新药物研发验证



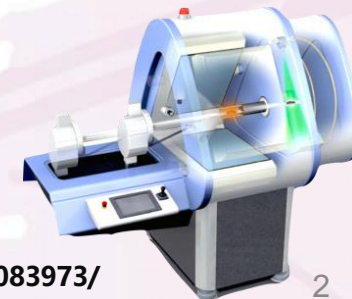
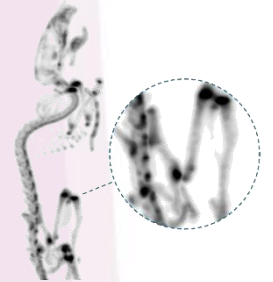
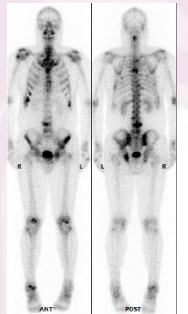
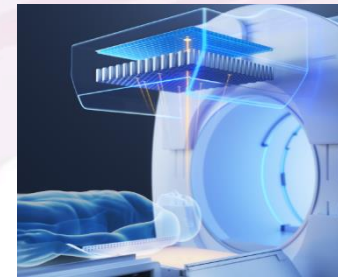
核素标记药物



靶向分子示踪



体外探测光子
三维图像重建



1. 经济合作与发展组织OECD官方网站统计数据 <https://stats.oecd.org/Index.aspx>

2. Preclinical Tomography System Market Report, marketresearch公司市场统计报告, <https://www.marketresearch.com/QYResearch-Group-v3531/Preclinical-Tomography-System-Company-Regions-12083973/>

核医学在临床诊断中的应用

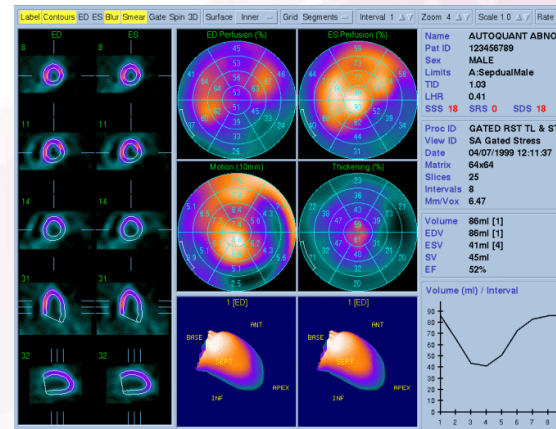
- 核医学成像广泛用于**肿瘤、心血管疾病、脑血管疾病等重大疾病诊断。**



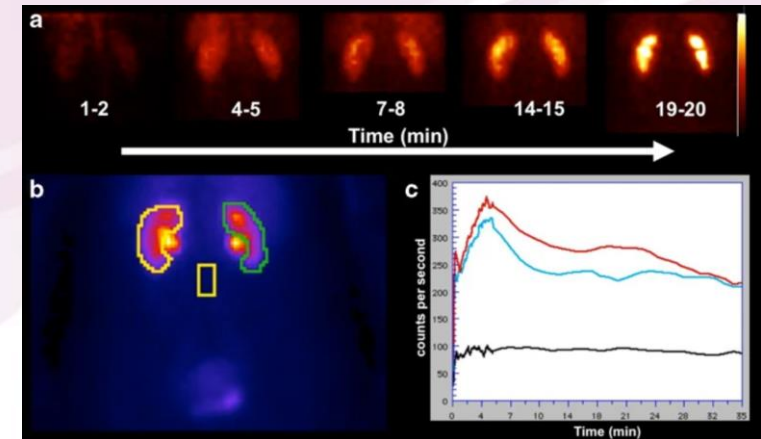
PET FDG肿瘤代谢显像



SPECT MDP肿瘤骨转移显像

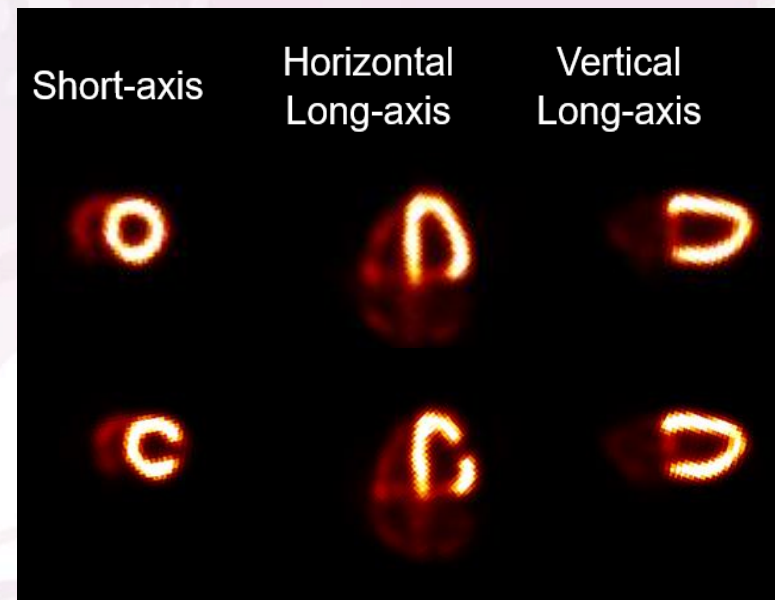
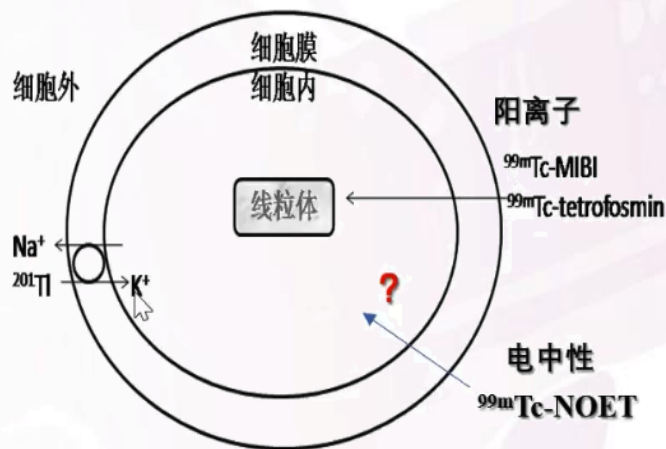
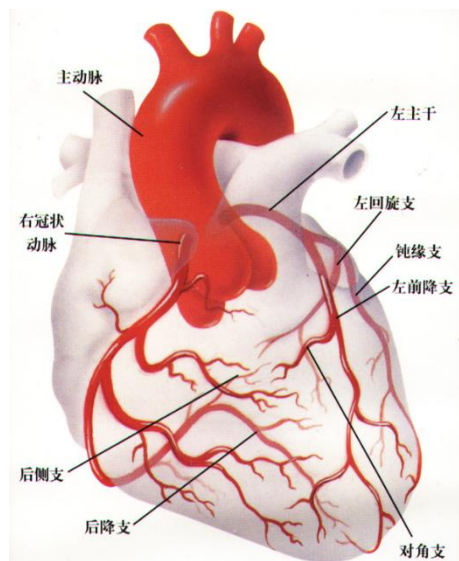


SPECT MIBI
心肌灌注显像



SPECT DTPA
动态肾功能显像

- MIBI(甲氧基异丁基异腈)药物:
 - 被冠脉“灌注”至心肌细胞被线粒体摄取, 药物分布反应冠脉向心肌供血情况
- ^{99m}Tc 放射性核素“标记”于MIBI药物:
 - 探测140 keV光子, 对MIBI药物分子分布成像



心肌供血正常

心肌缺血

SPECT MIBI心肌灌注显像

核医学：药物+仪器 -> 临床诊疗

^{99m}Tc -MIBI 心血流灌注成像
 ^{123}I -MIBG 心脏交感神经成像
 ^{99m}Tc -PYP 心肌淀粉病变成像



^{99m}Tc -MIBI 肿瘤细胞增殖成像
 ^{99m}Tc -HL₉₁ 肿瘤乏氧成像
 ^{99m}Tc -CNDG 肿瘤代谢成像
 ^{99m}Tc -Duramycin 肿瘤细胞凋亡成像



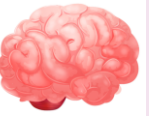
^{99m}Tc -MDP 全身骨成像
 ^{99m}Tc -HDP 全身骨成像
 ^{99m}Tc -WBC 全身炎症成像



^{131}I 甲状腺合成代谢成像
 $^{99m}\text{TcO}_4^-$ 甲状腺摄取成像



^{99m}Tc -ECD 脑血流成像
 ^{99m}Tc -HMPAO 脑血流成像
 ^{123}I -DAT 多巴胺转运蛋白成像
 ^{123}I -IMZ 神经受体成像



^{99m}Tc -DMSA 肾皮质成像
 ^{99m}Tc -DTPA 肾动态成像
 ^{99m}Tc -EC 肾小管分泌成像



^{99m}Tc -Technegas 肺通气成像
 ^{99m}Tc -DTPA 肺通气成像
 ^{99m}Tc -MAA 肺灌注成像



^{99m}Tc -RBC 肝血流成像
 ^{99m}Tc -HIDA 肝动态摄取成像
 ^{99m}Tc -GSA 肝功能成像

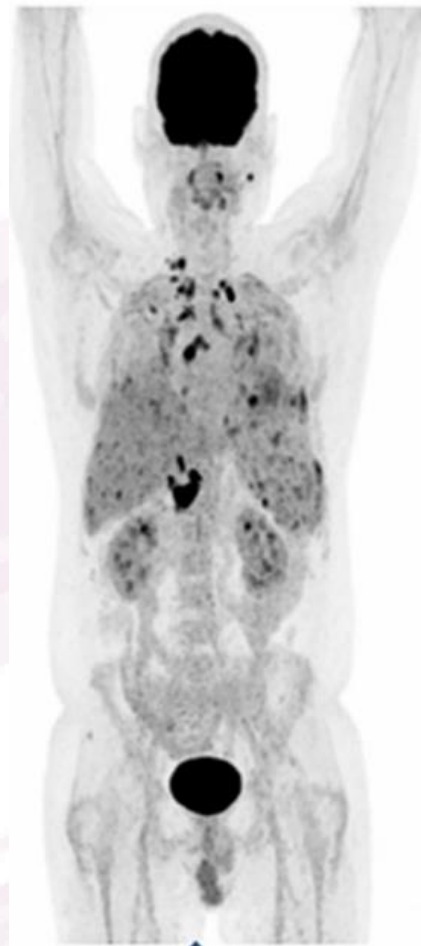
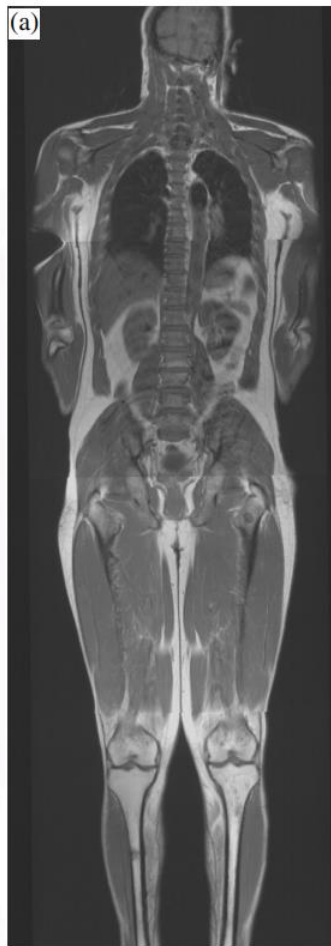
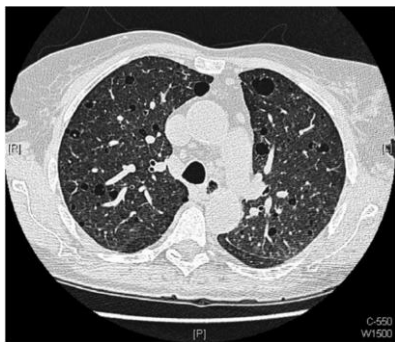


CT: 0.25~0.5 mm

MR: 1~2 mm

PET: 4~6 mm

SPECT: 10~20 mm



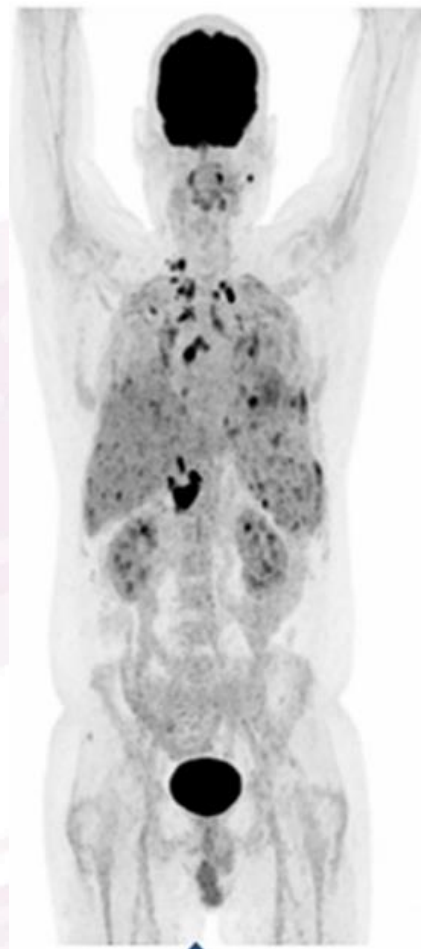
- 先进的分子影像理念

- 落后的物理性能瓶颈

- NuUnclear Medicine

PET: 4~6 mm

SPECT: 10~20 mm

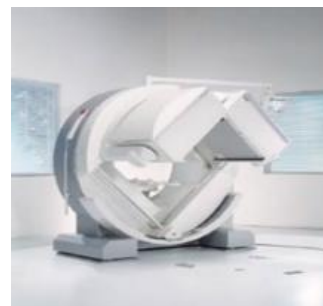


单探头SPECT

双探头SPECT

全环SPECT

物理结构



探测器

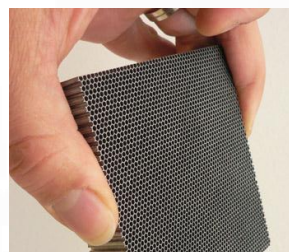


NaI(Tl)探测器
(固有分辨率 3~4 mm)



CZT探测器
(固有分辨率 1~2 mm)

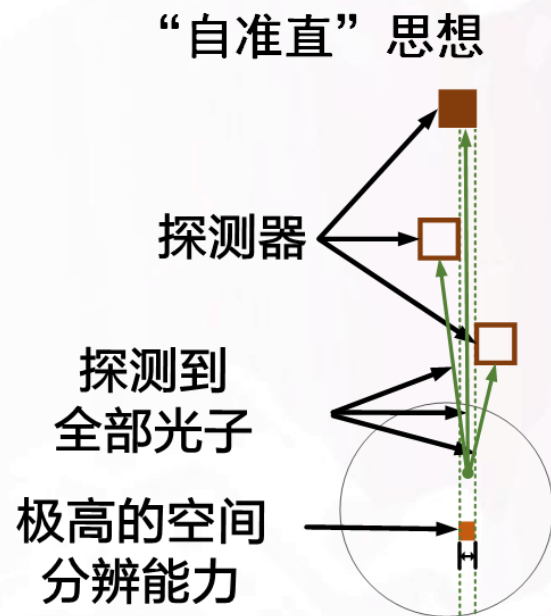
准直器



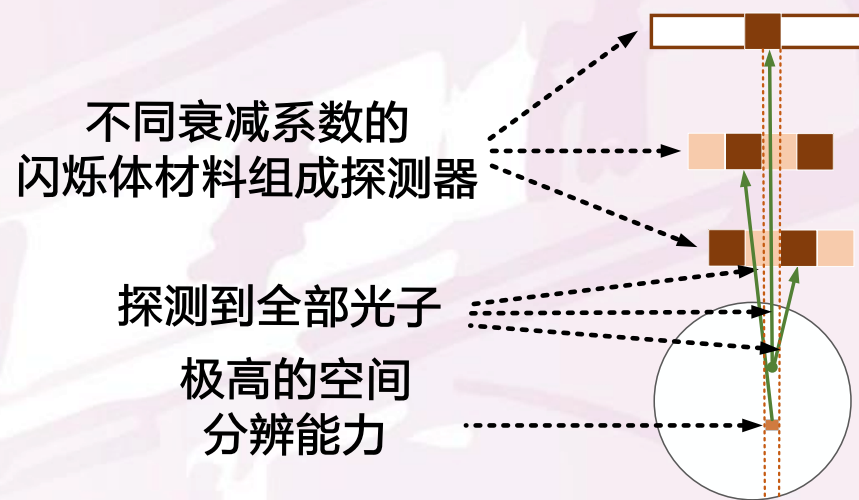
铅、钨制重金属准直器
(光子吸收比例 > 99.9%)

	NaI双探头 SPECT	CZT双探头 SPECT	CZT全环 SPECT
分辨率	10~20 mm	7~10 mm	5~7 mm
探测效率	0.01% ~ 0.02%	0.02%	0.1%

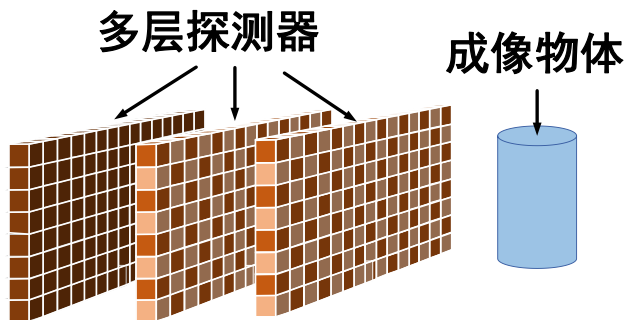
- 机械准直器是SPECT的主要**技术瓶颈**
- **自准直** — “用探测器做准直器”
- 构建三维稀疏探测器阵列
- 既形成高分辨率的准直效果，又不以损失光子为代价
- **使分辨率和探测效率同时提升**



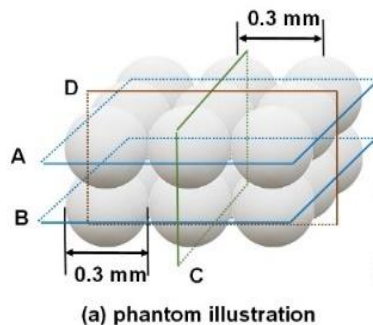
自准直SPECT系统结构



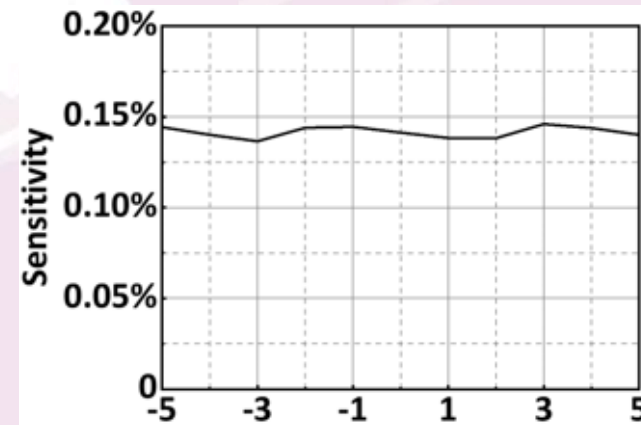
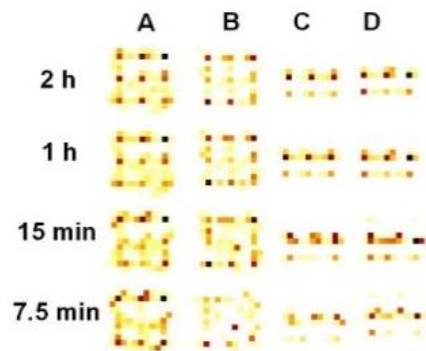
自准直SPECT原理装置验证



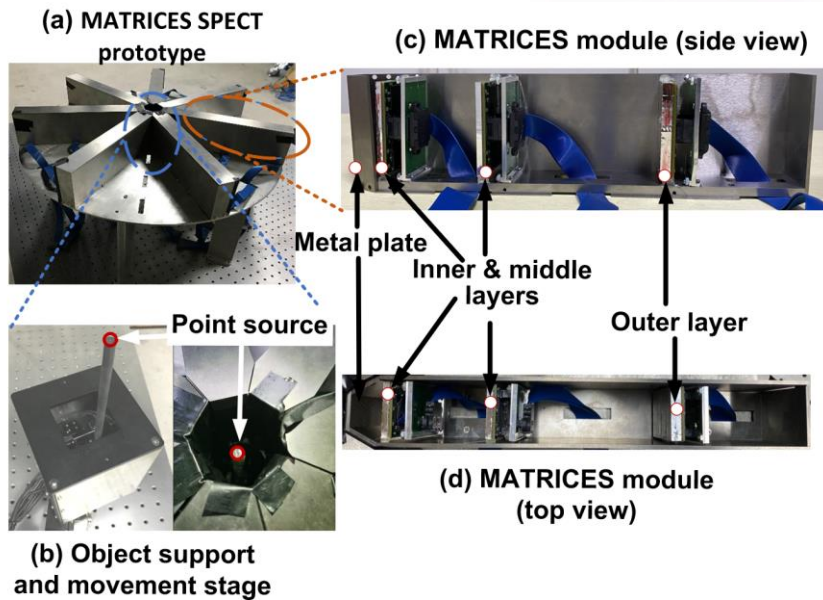
多层探测器，空间分离排列
前层探测器对后层形成自准直



0.32 mCi总活度

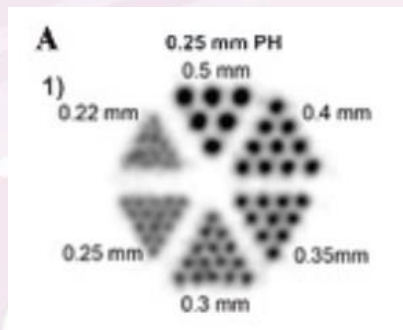


3 cm视野，0.1mm分辨率，0.14%探测效率



对比：目前世界最好水平的商业小动物U-SPECT系统：
3 cm视野，0.25 mm分辨率，0.034%探测效率

自准直SPECT原理验证装置





自准直SPECT原理验证论文发表于IEEE Transactions on Medical Imaging期刊 (2021 IF = 10.048, DOI: 10.1109/TMI.2021.3073288)

期刊编委美国UIUC大学Lingjian Meng教授评价:
“极具创新性 (significant novelty)”

Decision Letter (TMI-2020-2358)

From: lesleying@ieee.org
To: maty@tsinghua.edu.cn, tianyum@gmail.com
Subject: Decision on IEEE TMI-2020-2358
Body: Self-collimating SPECT with multi-layer interspaced mosaic detectors - TMI-2020-2358

Associate Editor: Meng, Ling-Jian
Comments to the Author:
Dear Authors, please see attached review comments for your revised manuscript. In general, the reviewers recognized that the collimation technique being explored in this manuscript carries significant novelty and is certainly of interest to the readers of TMI. The latest revision has addressed most of the previous comments, and the quality of the presentation is much improved. The reviewers have raised several major and minor critiques for further improving your manuscript. If you could, please carefully address these items and provide an item-by-item response to the reviewers. We would look forward to receiving your further revision.

Reviewer 1: “本工作是整条研究路线的奠基性工作”

setup. The manuscript is well structured, written with scientific rigor, and reads well. **This work can serve as a foundation for an entire line of research**

Reviewer 2: “引人入胜的工作，思路创新，做出了原创贡献”

1. In term of scientific merit, **this is an interesting work**, presenting **an innovative concept**, name self-collimation, for SPECT imaging applications. The proposed self-collimation architecture presents several
2. The paper proposes an **original contribution** in the field of collimation systems for SPECT applications, trying to **overcome the traditional tradeoff between spatial resolution and sensitivity, that represents one of the main problems/limitations** in SPECT imaging. <1

Reviewer 3: “论文的思想 and 结果有望带来SPECT技术革新”

This manuscript has been described to **present new concept** of self-collimating SPECT without active metallic collimator. **The concept and results of this manuscript are so interesting** and **have a potential to contribute to innovation of SPECT imaging technology**. The

“鱼”与“熊掌”兼得



中国科技网
stdaily.com

科技日报报系

首页 研习 新闻 前沿 国际 访谈 专题 时评 社区 English 5G 智能驾驶 大数据

科技日报报系

“鱼”与“熊掌”兼得 清华大学医工结合团队大幅提升SPECT分辨率和探测效率

2021-05-17 11:07:19 来源: 科技日报 作者: 于悦超 韩冬野 于紫月

中国科技网讯 (通讯员于悦超 韩冬野 实习记者于紫月) 5月11日, 记者从清华大学附属北京清华长庚医院了解到, 由清华大学工物系马天宇副教授、刘亚强研究员以及该医院核医学科主任何作祥教授等组成的医工结合团队, 创新了单光子发射计算机断层成像(SPECT)的成像机理, 有望大幅提升SPECT技术的分辨率和探测效率。该研究成果近日发表在《IEEE医学成像汇刊》上。

SPECT是核医学影像的重要组成部分, 是对病人体内发射的 γ 射线进行成像, 广泛应用于肿瘤骨转移、心脑血管疾病、肾功能疾病、内分泌相关等重大疾病诊断, 及放射性核素治疗药物的精准剂量评估。如骨显像对各种骨骼疾病的诊断和治疗效果的评价有重要价值, 可早期发现恶性肿瘤患者骨转移病灶。

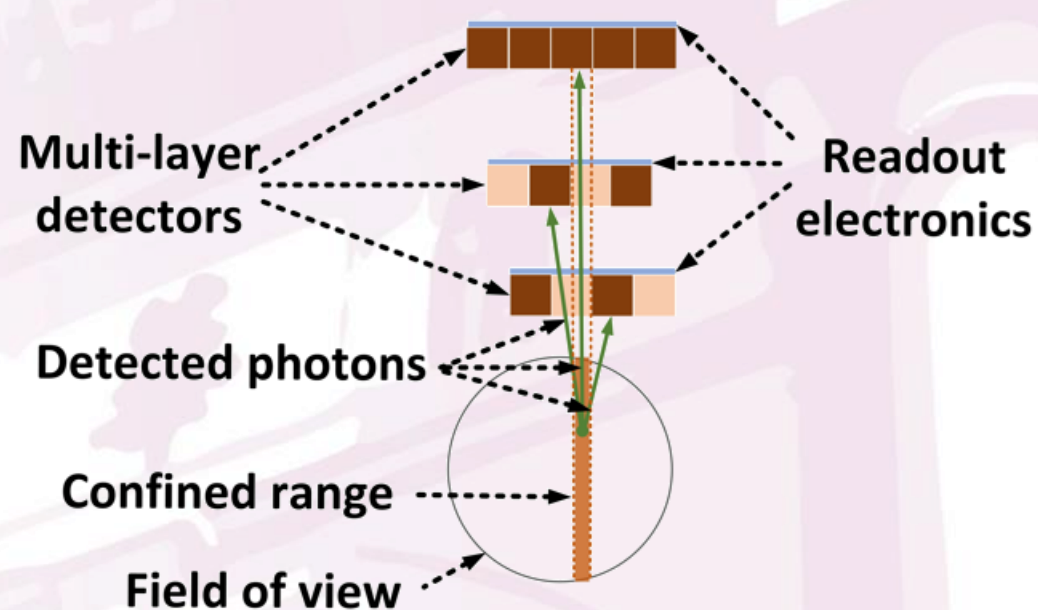
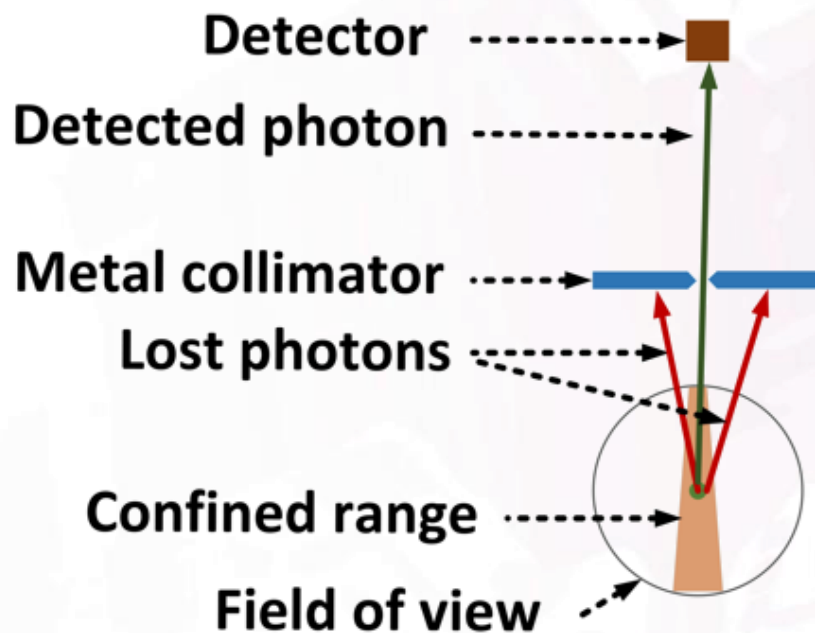
传统SPECT技术的空间分辨率和探测效率是相互制约、不可兼得的“鱼”和“熊掌”, 因此严重制约了其影像学诊断价值和临床应用范围。其中, 由铅、钨等重金属制成的机械吸收式准直器既是SPECT成像必不可少的成像部件, 也因其吸收了99.9%以上的光子, 使得分辨率和探测效率性能互相制约, 导致SPECT性能落后, 为此, 何作祥创新性地提出了“去掉准直器”的SPECT成像设想。

模拟验证人脑自准直SPECT达到0.5mm分辨率和3.88%探测效率

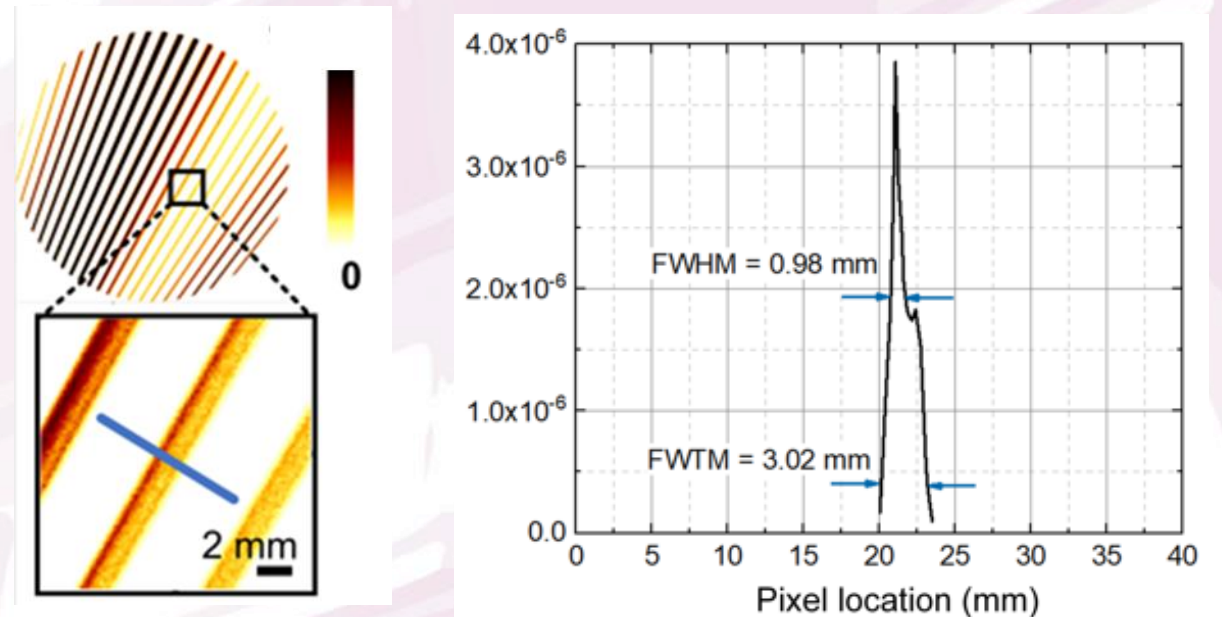
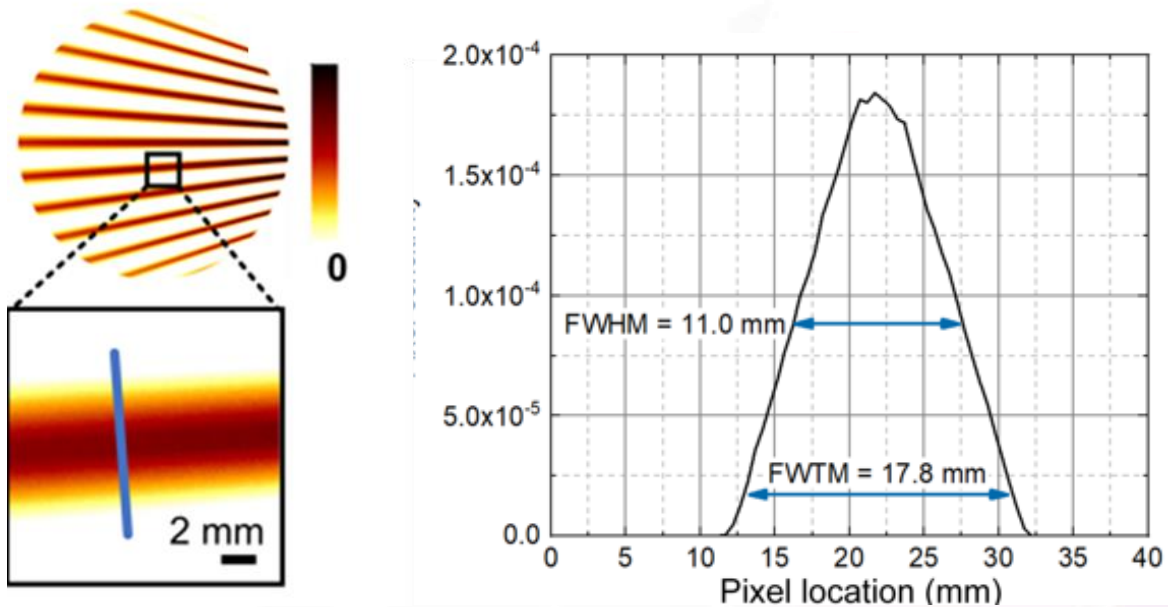
(a) MATRICES SPECT prototype (b) MATRICES SPECT design schematic (c) MATRICES module (side view) (d) simulated human brain SPECT

Transaxial position (mm)	Sensitivity (%)
-100	0
-50	0
0	3.88
50	0
100	0

- 自准直SPECT为什么能获得超高的空间分辨率?
- 空间分辨率取决于探测器空间响应函数 (DRF) 的特性
 - 传统机械准直SPECT: DRF 宽度 \leftrightarrow 准直孔径 \leftrightarrow 分辨率和探测效率的互相制约
 - 自准直SPECT: DRF 宽度 \leftrightarrow 合理设计的探测器单元空间排布

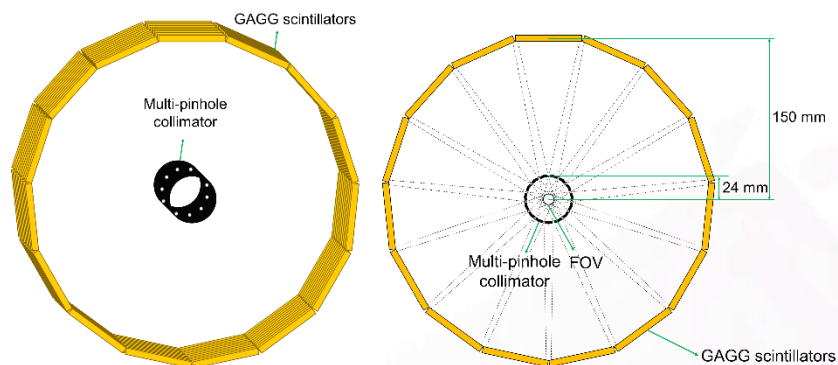


- 传统SPECT成像理论仅提取 DRF 的宽度特性用于分辨率计算
- 进一步提出：空间分辨率还取决于DRF的**边缘陡峭程度**
 - 自准直SPECT利用探测器和方孔金属板的边缘准直，具有更“陡”的DRF

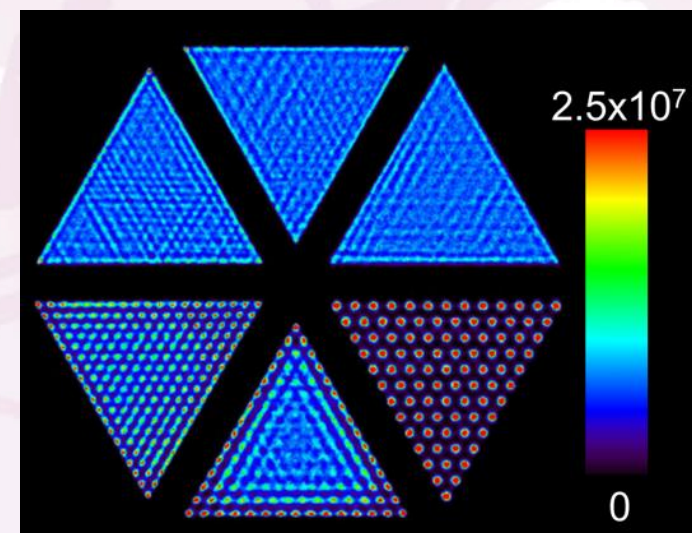
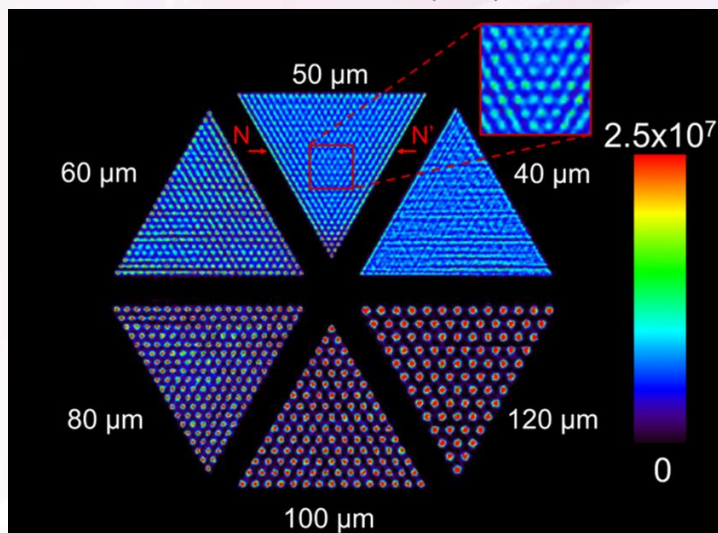
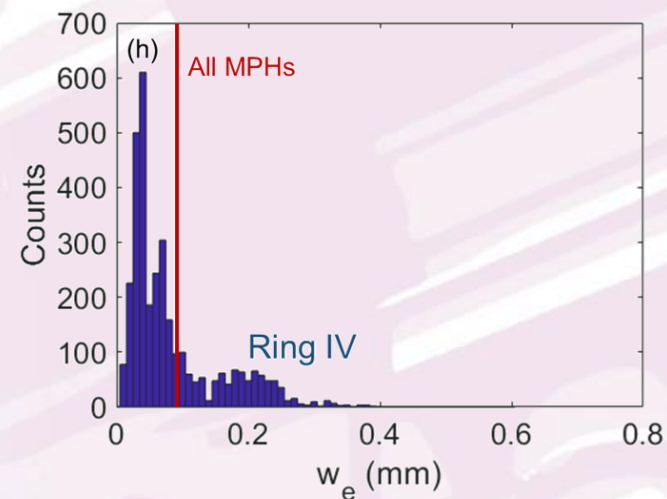
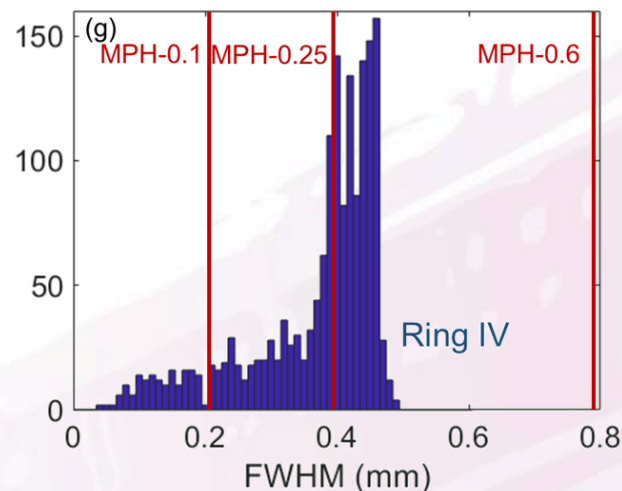
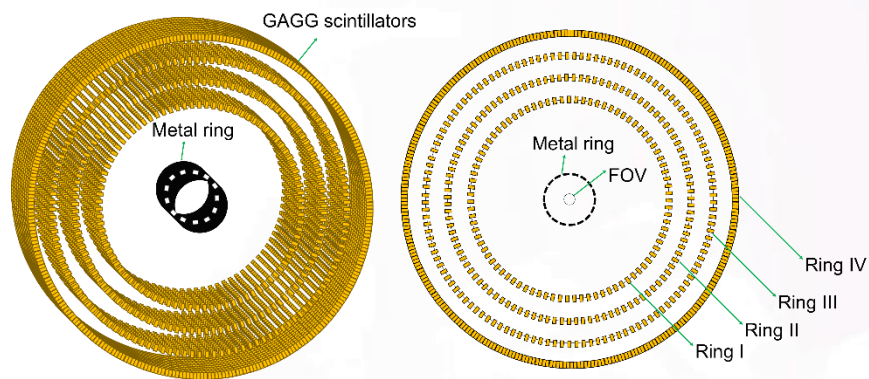


- 自准直SPECT的探测器数目更多、DRF既“窄”又“陡”，因而分辨率显著提升

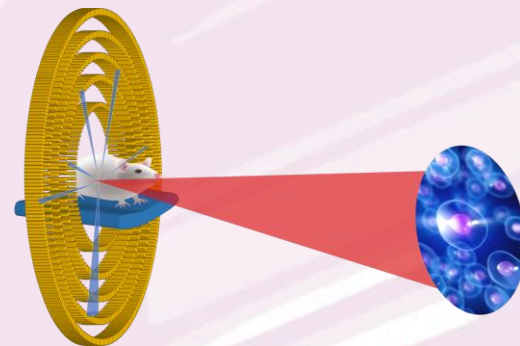
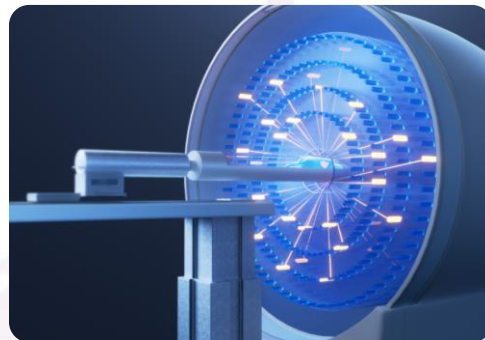
多针孔SPECT



自准直SPECT

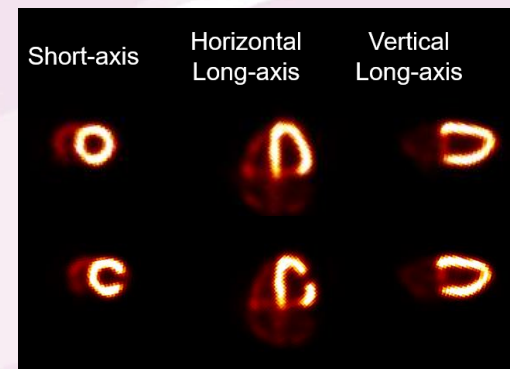
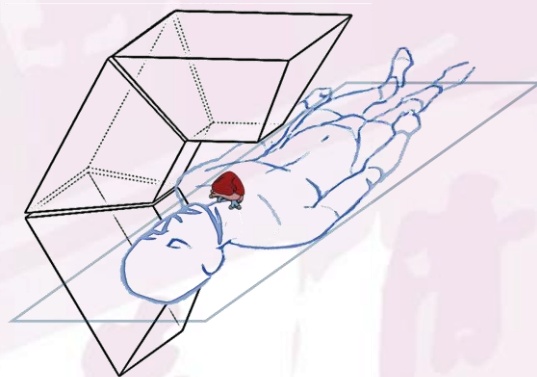


极高空间分辨率

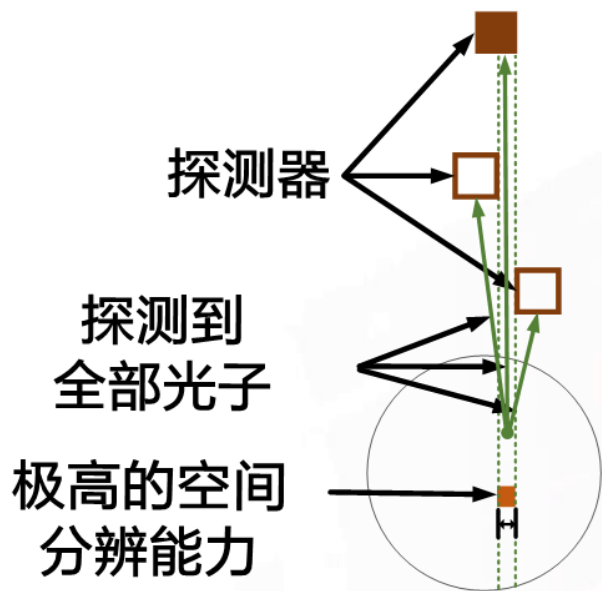
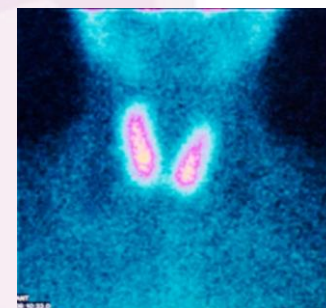


“自准直”思想

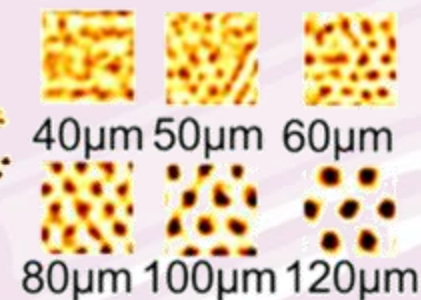
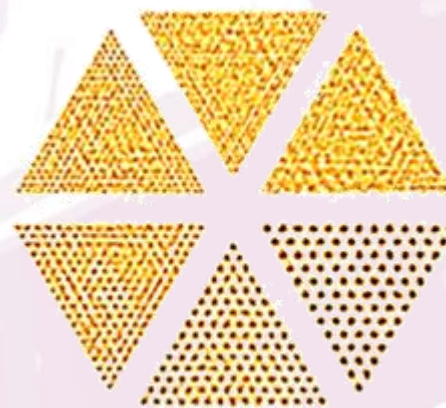
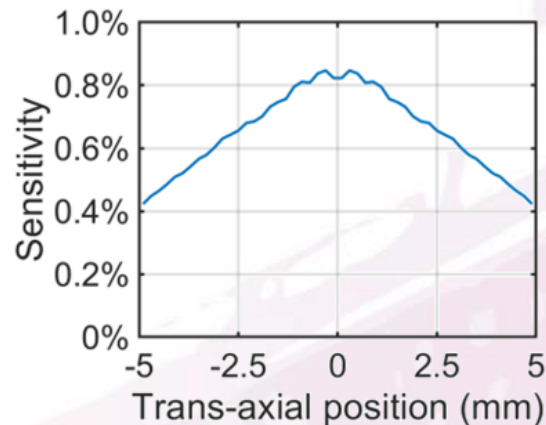
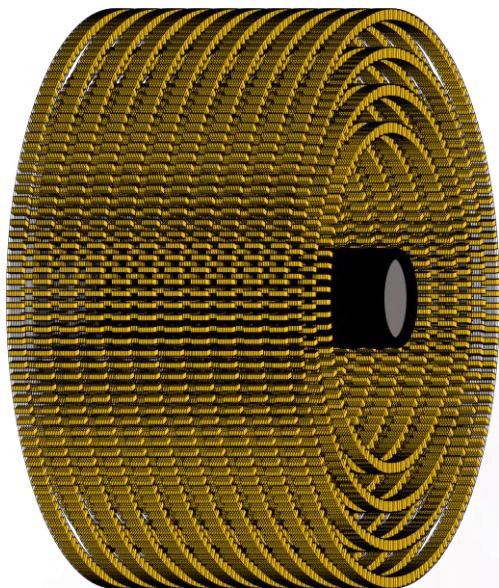
极高探测灵敏度



极高设备便携性



极高分辨率小动物自准直SPECT系统-设计和模拟评估

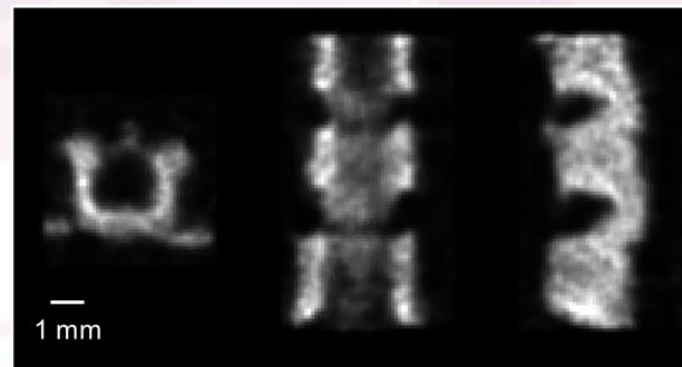


平均探测效率
0.41%

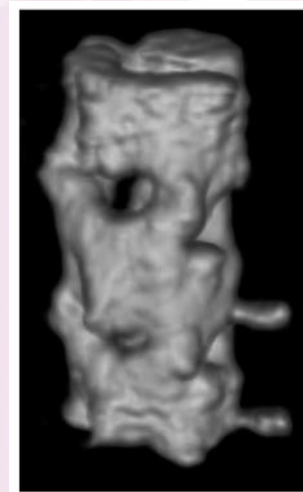
有限活度/采集时间
空间分辨率 80~100 μ m

三维稀疏排列的16,800个GAGG(Ce)闪烁
晶体单元组成自准直小动物SPECT系统

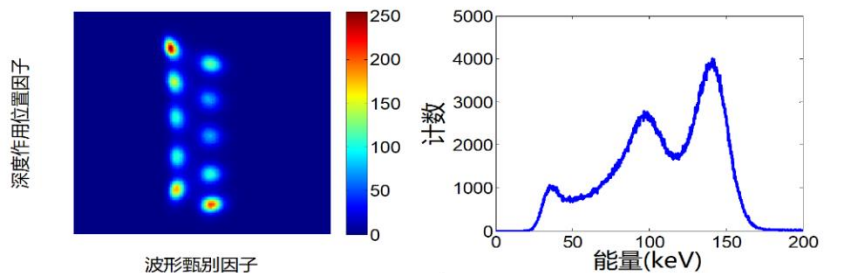
Zhang et al SNMMI 2020
Manuscript submitted to IEEE TMI



清晰分辨小鼠脊椎骨细微结构



三维稀疏阵列探测器模块



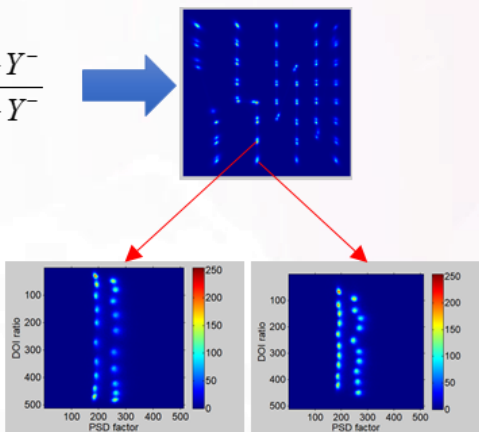
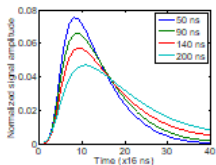
位置加权

$$X = \frac{X^+ - X^-}{X^+ + X^-}, Y = \frac{Y^+ - Y^-}{Y^+ + Y^-}$$

双端读出

$$Z = \frac{ET - EB}{ET + EB}$$

波形甄别



小动物自准直SPECT样机装置



设计指标:

- 孔径: 7 cm
- 小鼠成像视野: 3 cm
- 大鼠成像视野: 5 cm
- **空间分辨率: ≤ 0.1 mm**
- **探测效率: $\geq 0.5\%$**

(现有最好商业系统:

0.25 mm @ 0.034%))



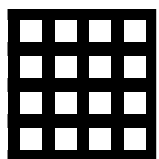
- 成像系统信噪比同时取决于系统探测效率和测量事件的信息量
- 信噪比定量评估理论模型

信噪比 \rightarrow DRF的互相关性

$$C_W = A'WA$$

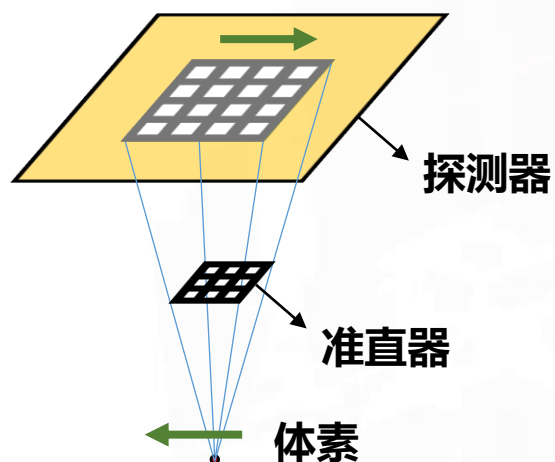
- DRF的空间稀疏性
- DRF的空间移变特性
- DRF的自相关性

多针孔系统

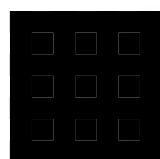


不同体素的
DRF

非空间稀疏 (X)
空间移不变 (X)
强自相关 (X)

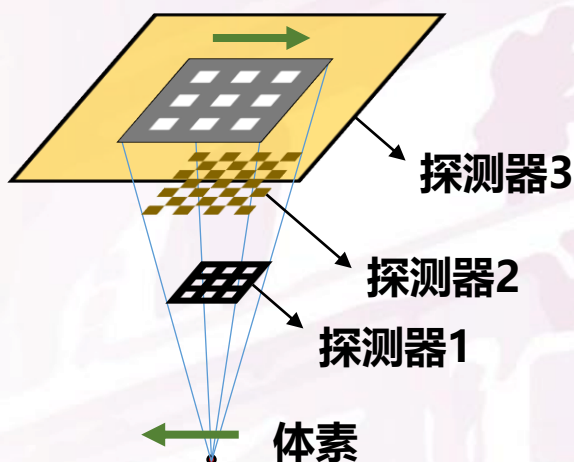


自准直系统

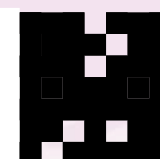


不同体素的
DRF

空间稀疏 (✓)
空间移变 (✓)
强自相关 (X)

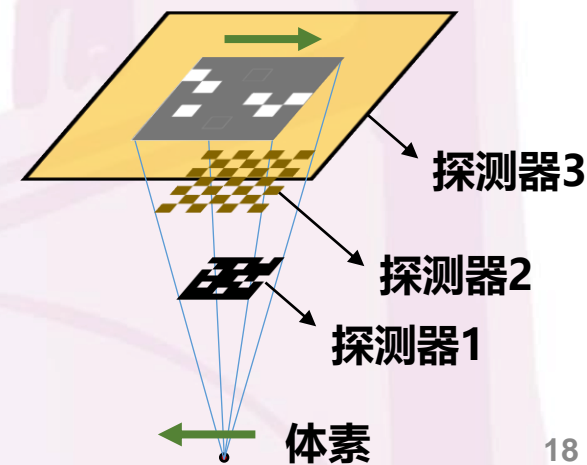


乱序排布-自准直系统

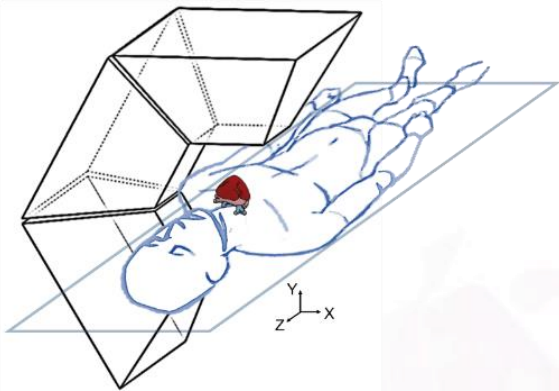


不同体素的
DRF

空间稀疏 (✓)
空间移变 (✓)
弱自相关 (✓)



快速心脏成像系统设计方案



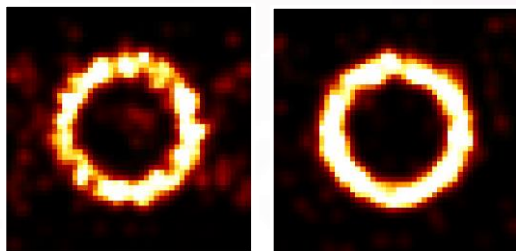
图像重建验证乱序排布系统性能显著提升

均匀排布 乱序排布

排布方案

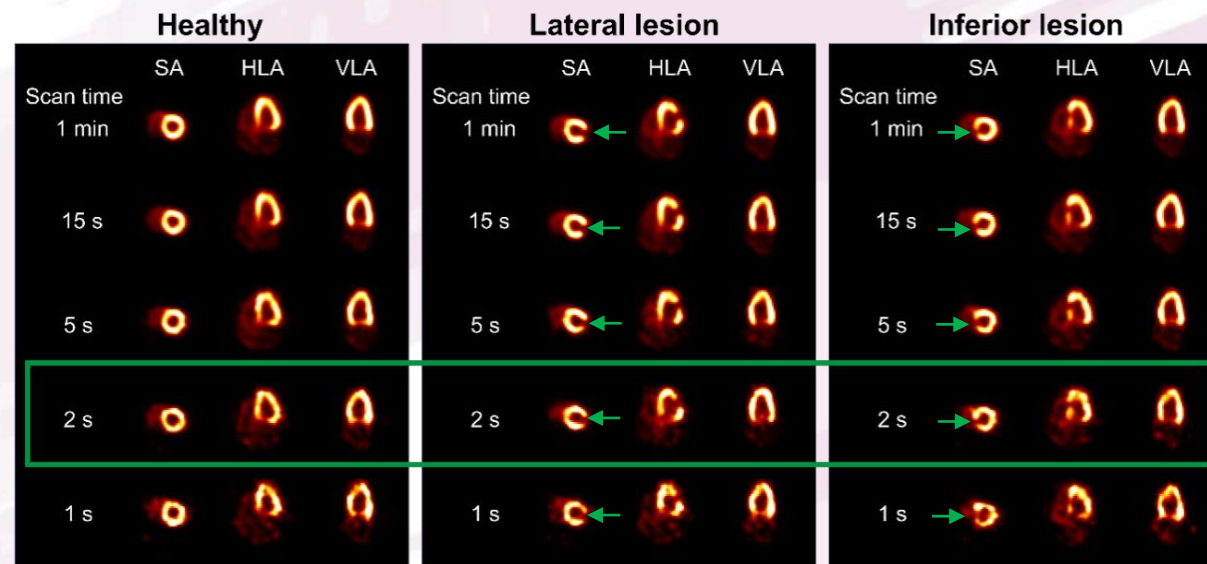


重建图像



蒙特卡模拟性能评估

	空间分辨率	探测效率	成像时间
国际前沿水平	6-15 mm	0.05%-0.2%	2-5 min
自准直SPECT	4 mm	0.68%	2 s



- 使临床心脏SPECT成像速度由数分钟提升至**数秒**
- “冻结”呼吸，提高诊断精度

极高探测效率快速心脏SPECT成像系统

SNMMI年会官方网站发布**热点新闻**，标题为**“革命性技术缩短心脏扫描时间，获取高质量SPECT图像”**。



Donate | Join/Renew | Store | View Cart | Log In

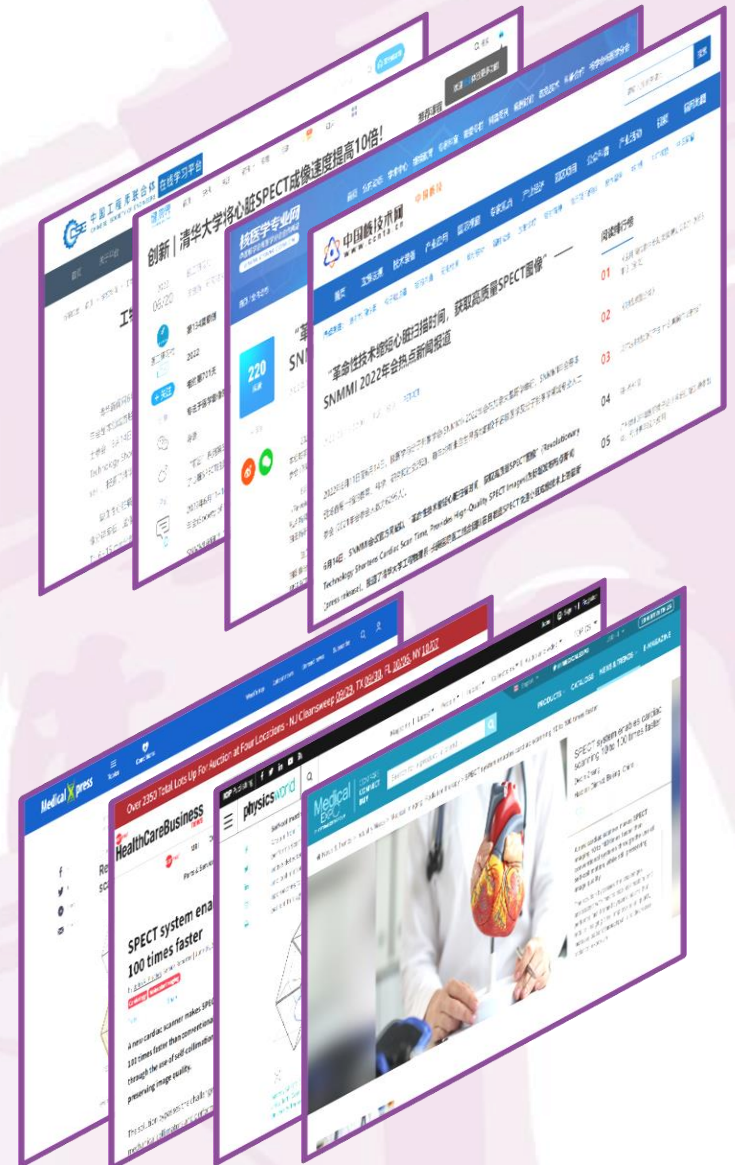
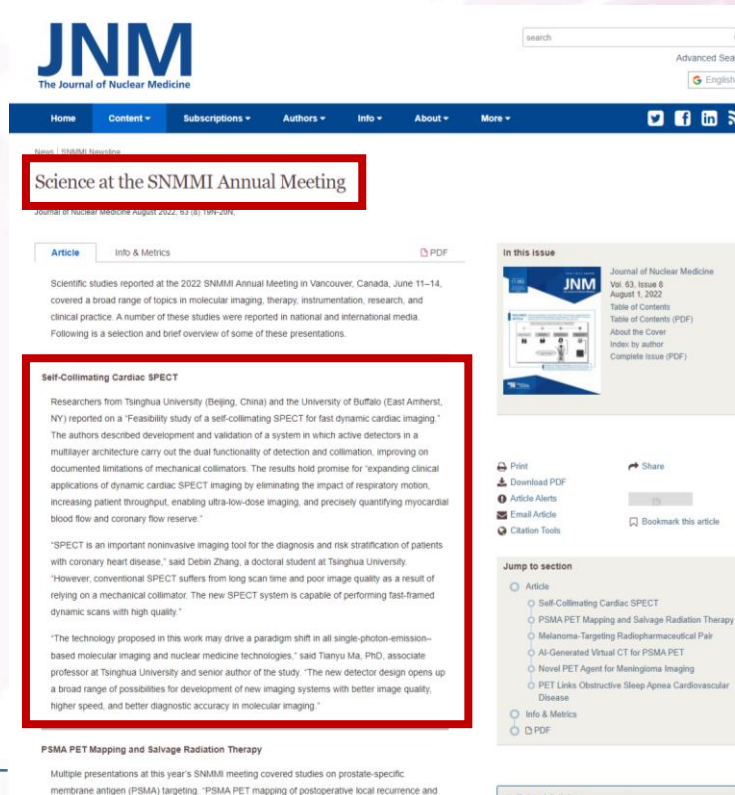
Revolutionary Technology Shortens Cardiac Scan Time, Provides High-Quality SPECT Images

June 14, 2022

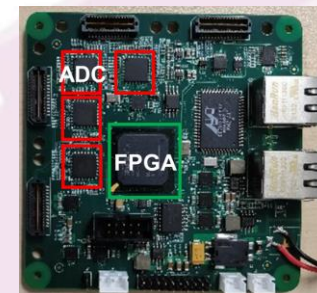
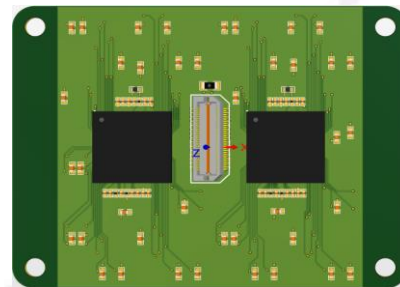
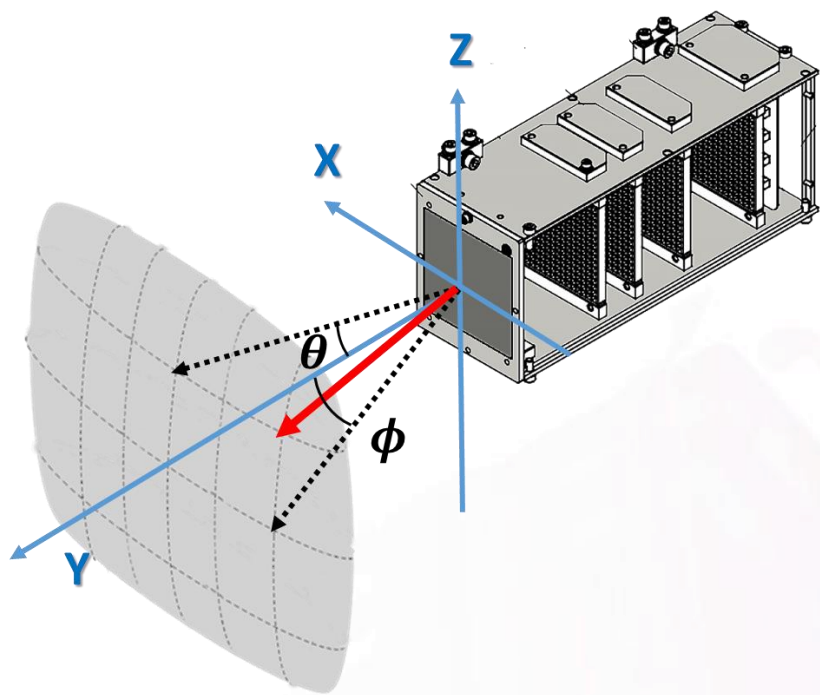
Reston, VA — A cardiac SPECT imaging system performs scans 10 to 100 times faster than current SPECT systems, according to new research presented at the Society of Nuclear Medicine and Molecular Imaging 2022 Annual Meeting. The advantages of self-collimation SPECT include dramatically shortened scan time, better image quality, increased patient throughput, and reduced radiation exposure to patients.

Heart disease—which includes heart attack, heart failure and arrhythmias—is the leading cause of death among adults in the

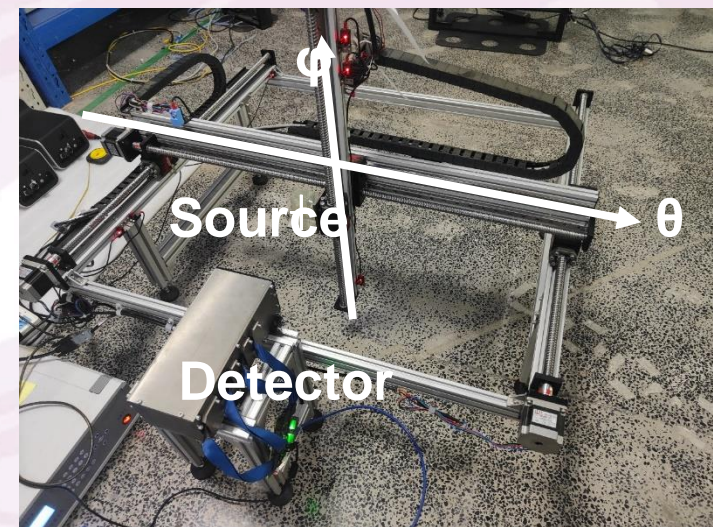
领域顶级期刊 J. Nucl. Med.(IF=11.082) 在报道本次会议的“Science at the SNMMI Annual Meeting”专栏中，本工作在6项代表性进展中被**排在首位**。

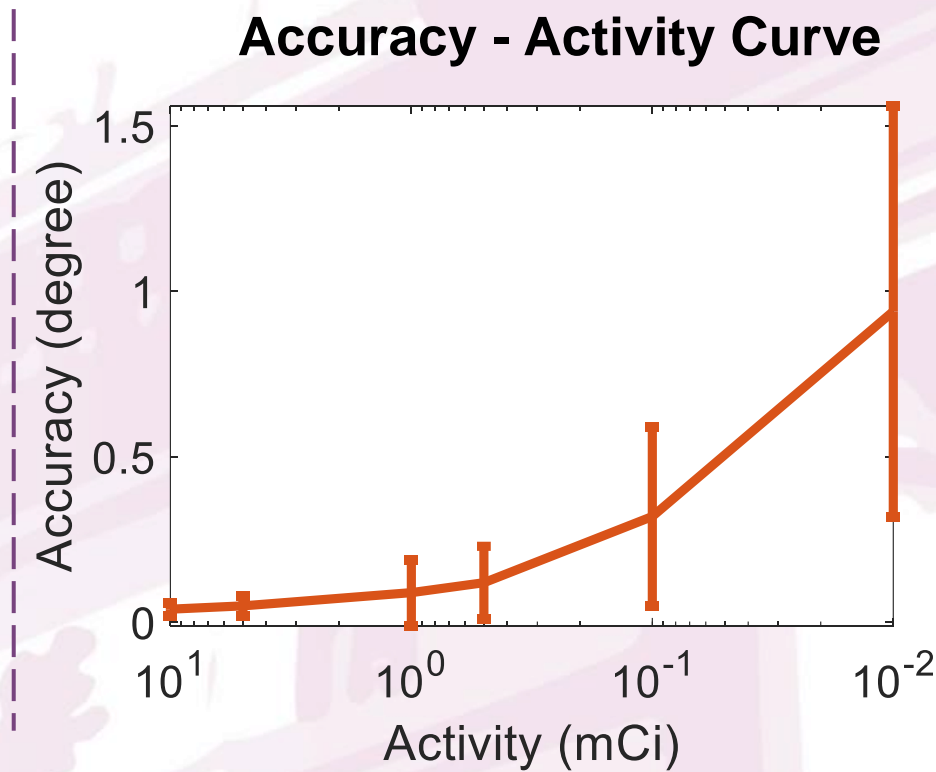
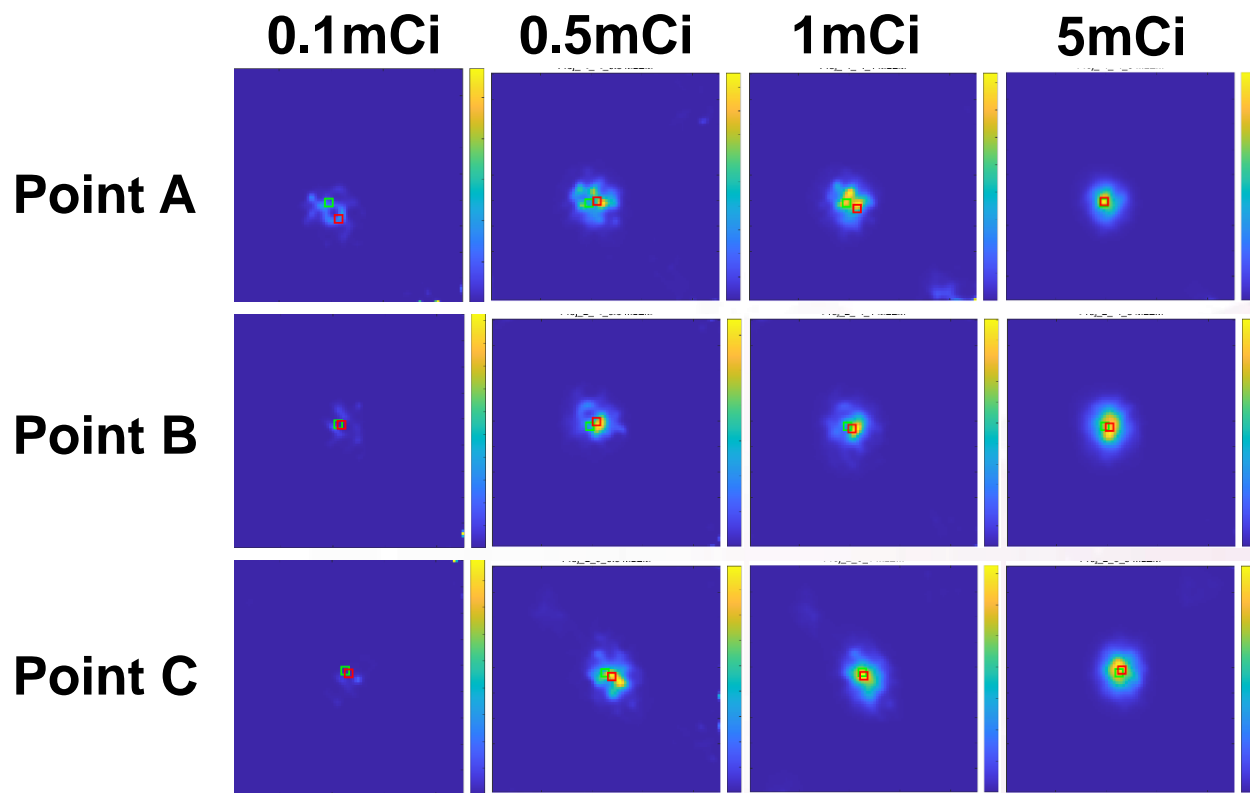


高便携性、高分辨率自准直伽马相机

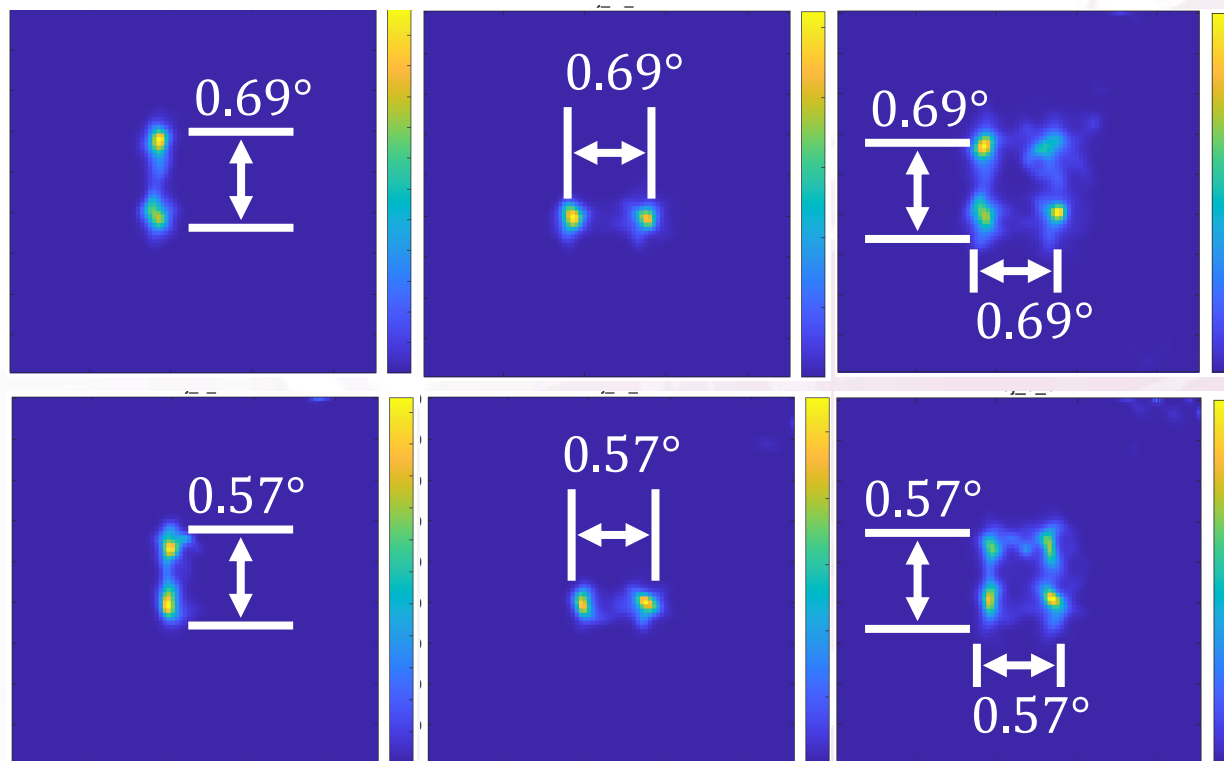


四层GAGG(Ce)单元组成稀疏排列的自准直伽马相机探测器

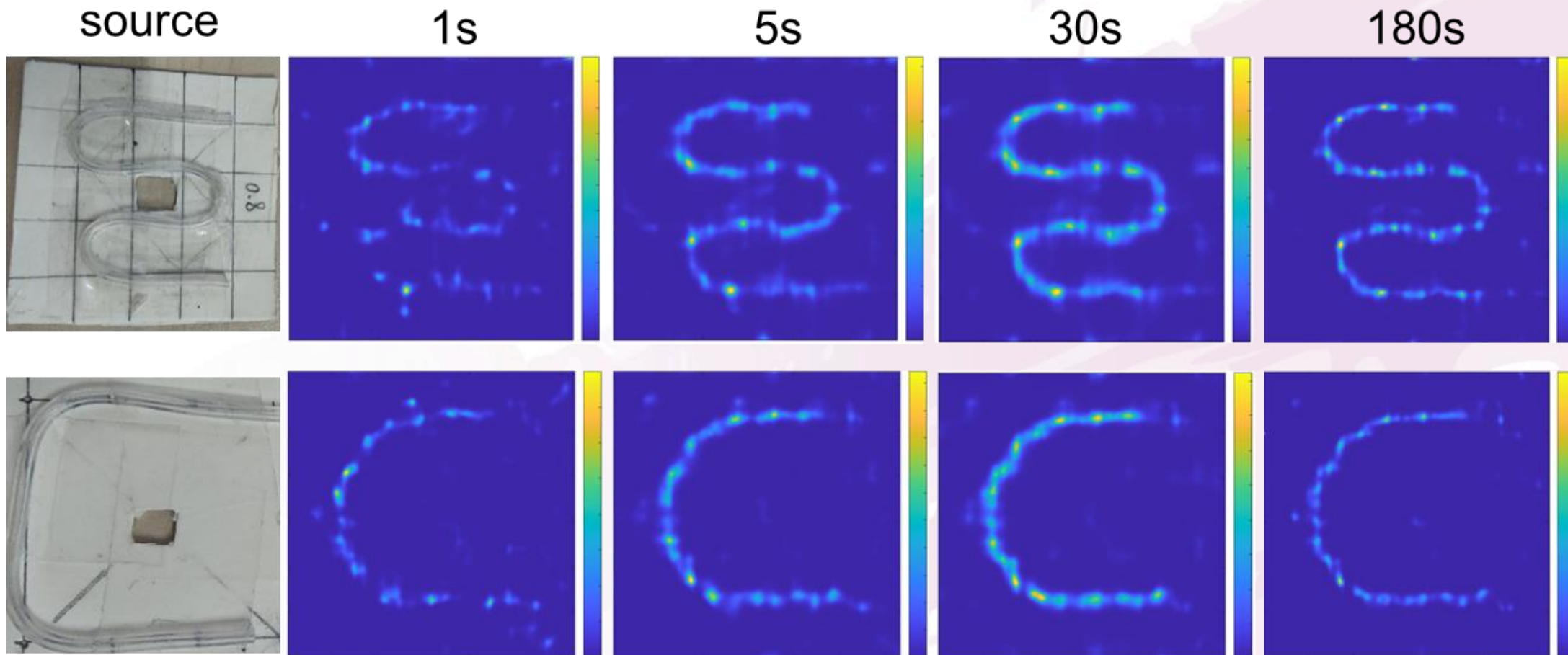




对0.1 mCi的^{99m}Tc点源, 在1m距离、1s采集时间内获得精确定位图像



对1m处相距 0.57° (9.9 mm) 的 ^{99m}Tc 双点源, 1s采集时间内获得精确分辨图像

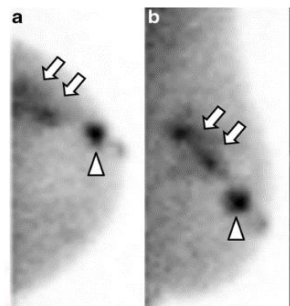


在10cm距离、5s采集时间内对活度0.35mCi(20 μ Ci/mm)的 ^{99m}Tc 线源形状精确成像

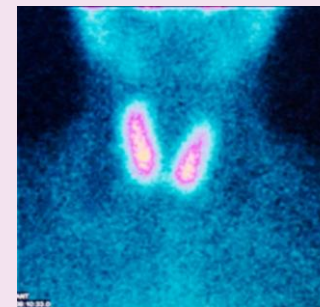
高便携性、高分辨率自准直直伽马相机



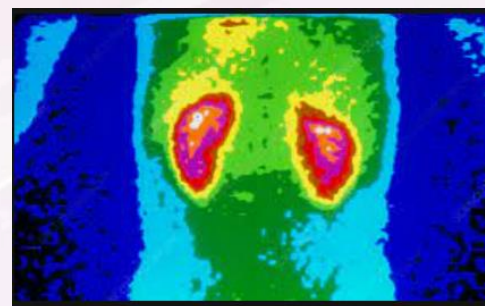
床旁支架式医用伽马相机



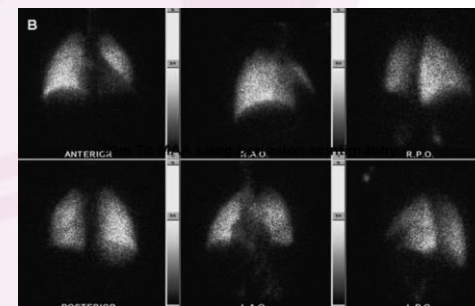
乳腺分子影像



甲状腺/甲状旁腺显像

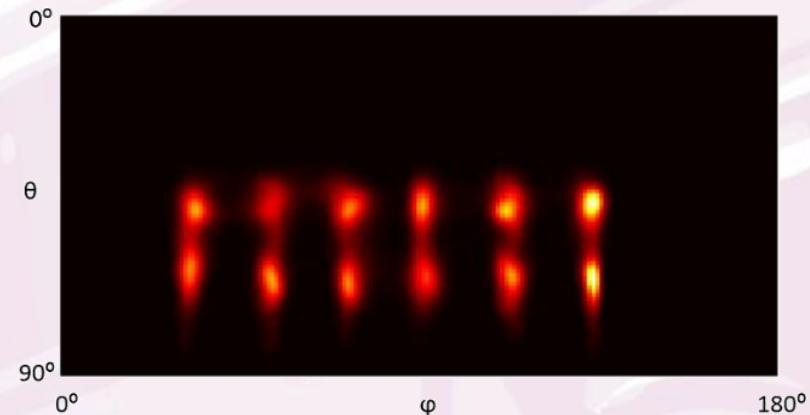
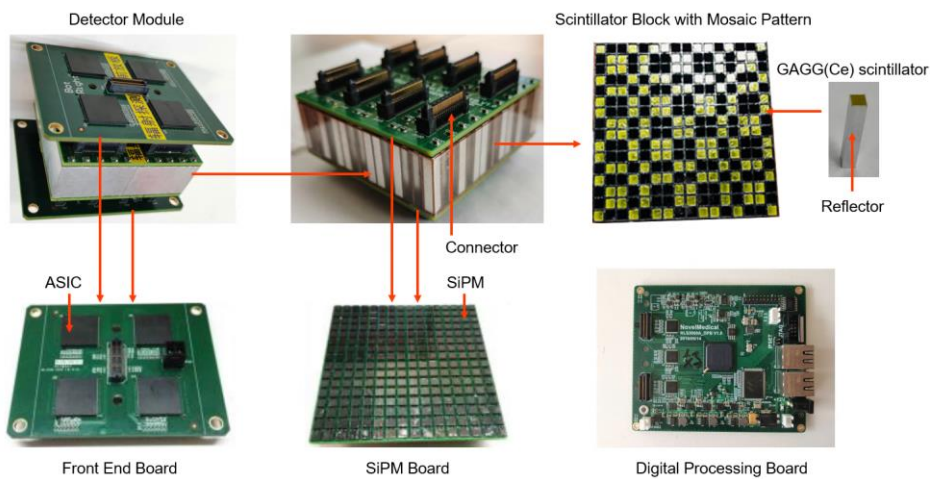


肾功能显像



肺通气/灌注显像

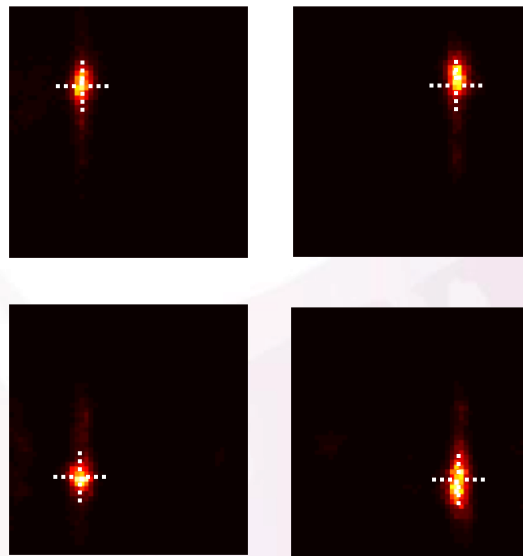
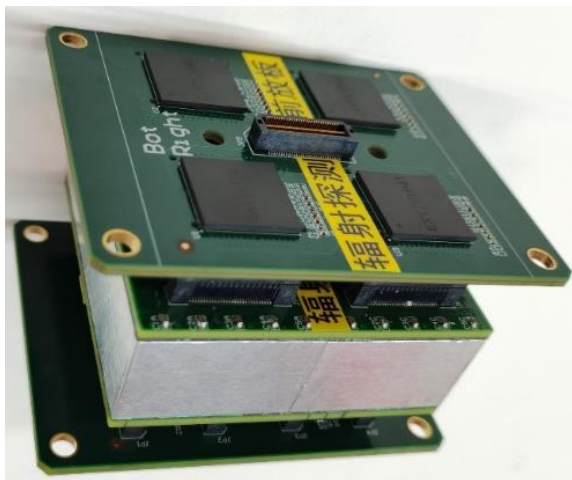
大视野、高动态性自准直伽马相机



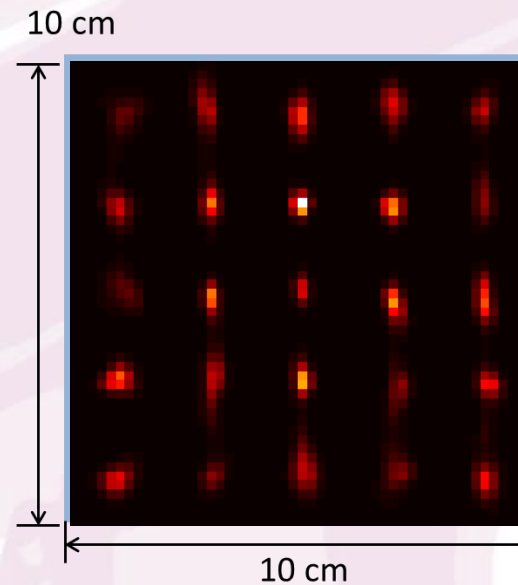
- 0.2 mCi Tc99m源
- 距离10 cm, 2.7 s成像

Hu et al. IEEE NSS/MIC 2021 (NSS2021最佳口头报告第一名)
Hu et al. NIMA 2022

大视野、高动态性自准直伽马相机



0.1mCi点源@15 cm
1s 采集时间
精确定位

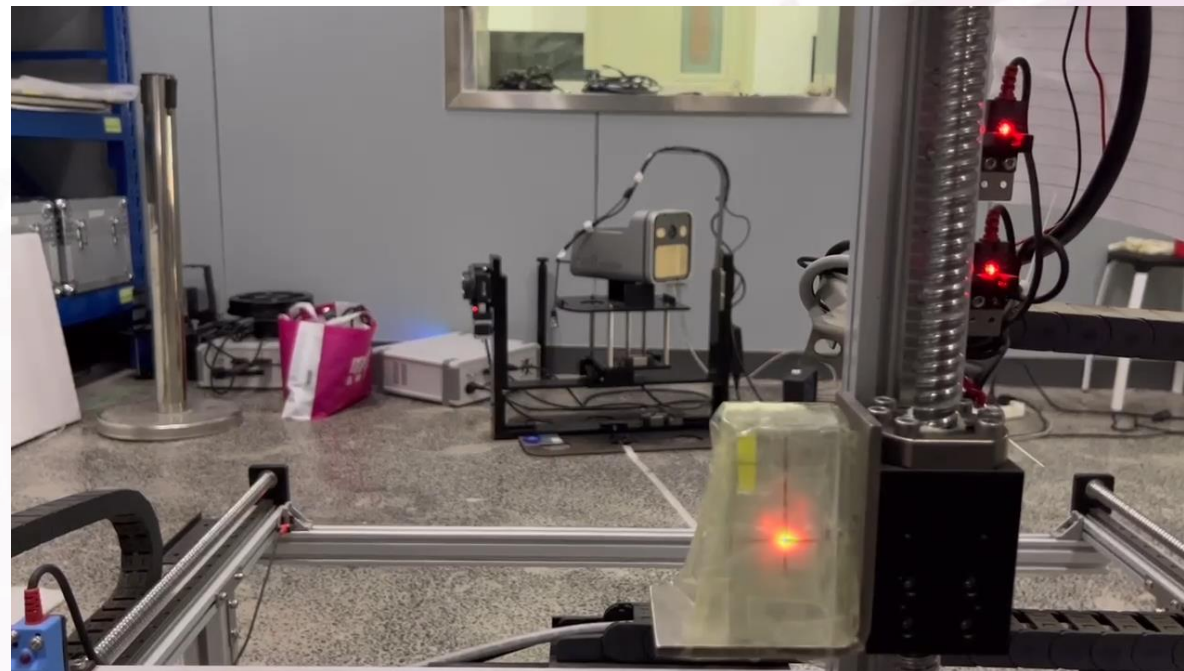
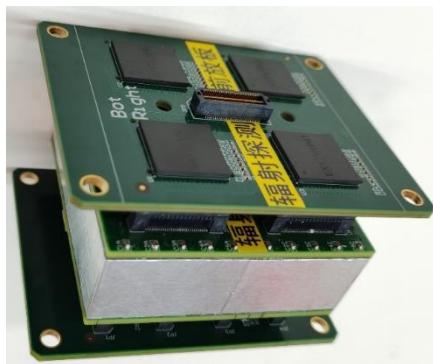


10 cm x 10 cm视野内
清晰区分5 x 5个点源

- 探测器技术方案和固有分辨率进一步提升

Hu et al. will be presented in IEEE NSS/MIC 2022

大视野、高动态性自准直伽马相机



0.1mCi点源
@15 cm
1s 实时跟踪
定位成像

探测器技术方案和固有分辨率进一步提升

Hu et al. will be presented in IEEE NSS/MIC 2022

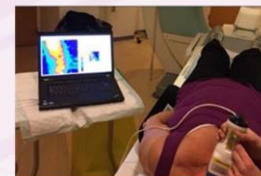
高便携性、高分辨率自准直直伽马相机



术中手持式医用伽马相机



肿瘤术中前哨淋巴结定位



肿瘤穿刺术引导

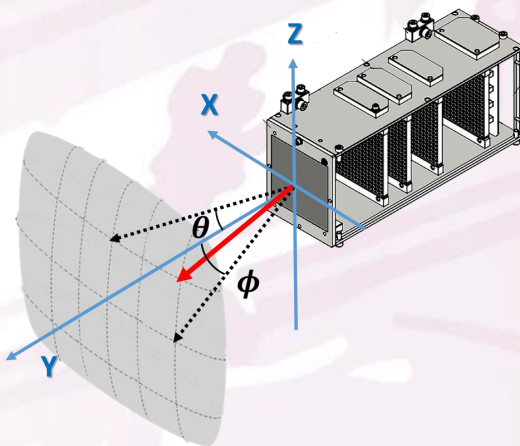
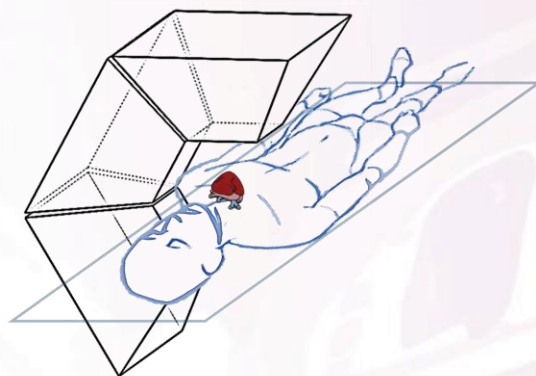
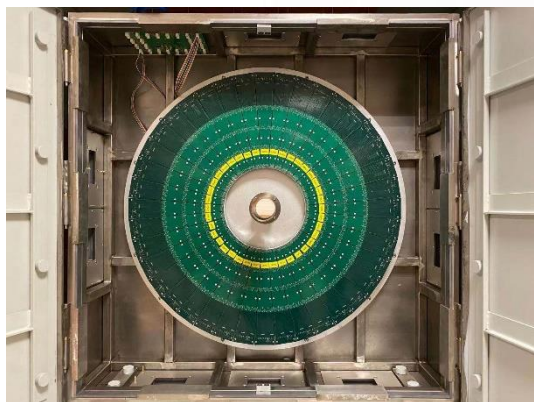


肿瘤切除术引导



粒子植入和内照射放疗
影像监测

- 提出原始创新的“自准直” SPECT成像思想
- 从机理上摆脱机械准直的分辨率-探测效率互锁瓶颈
- 发展高分辨率、高动态性、高便携性的核医学成像设备
- 在新的技术性能层面上发挥核医学分子影像的独到优势





清華大學
Tsinghua University

Thank you

