❖综述

Research progresses of 7.0T MRI for spinal and spinal cord diseases

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[**Abstract**] Due to core advantages including significantly improved resolution and signal-to-noise ratio, enhanced magnetic susceptibility effect and rapid imaging, 7.0T ultra-high-field MRI had gradually became an important tool for diagnosing and assessing spinal and spinal cord diseases, being expected to be widely used in clinical practice. The research progresses of 7.0T MRI for spinal and spinal cord diseases were reviewed in this article.

[**Keywords**] spine; spinal cord; magnetic resonance imaging
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7.0T MRI 用于脊柱脊髓疾病研究进展

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［**摘　要**］ 7.0T 超高场强 MRI 显著提升了分辨率和信噪比、增强了磁敏感效应增强及快速成像能力，逐渐成为诊断及评估脊柱脊髓疾病的重要手段，有望广泛用于临床。本文就 7.0T MRI 用于脊柱脊髓疾病研究进展进行综述。

［**关键词**］ 脊柱；脊髓；磁共振成像
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MRI 用于检测脊柱、脊髓和肌肉等部位病变具有突出优势；但脊髓结构特殊，直径仅约 1 cm，使传统 MRI 受限于部分容积效应而难以清晰显示其灰、白质分界等细微结构。7.0T MRI 具有可达 50～100 μm 的超高空间分辨率和较传统 3.0T MRI 提升 4～8 倍的信噪比(signal-to-noise ratio, SNR)，显示灰白质分界、微血管及中央管周围微水肿等细微结构能力较佳，可用于检测早期多发性硬化症(multiple sclerosis, MS)所致脊髓中央管微水肿、精确显示灰质前角神经元群[1]。但 7.0T MRI 用于临床尚面临 3 大关键挑战：①磁敏感伪影明显，使颈胸段失真程度较 3.0T MRI 升高约 2.4 倍，虽然采用优化梯度回波序列(如将回波时间缩短至 4 ms)可使伪影信号强度降低约 35%[1]，但作用究属有限；②受比吸收率限制，需调整脉冲序列参数控制射频能量；③存在运动伪影，需依赖门控技术或实时校正算法[2]。本文就 7.0T MRI 用于脊柱脊髓疾病研究进展进行综述。

1　7.0T MRI 技术优化与序列创新

1.1　结构成像

1.1.1　磁敏感加权成像(susceptibility weighted imaging, SWI)　相比 3.0T，7.0T 具有高空间分辨率和磁敏感效应[1]，以之行 SWI 显示脊髓细小静脉和检测创伤后微出血灶敏感度更高。针对脊髓海绵状血管瘤的研究[3]结果显示，以 7.0T SWI 相位值鉴别钙化与出血的准确率高达 92%，显著高于 3.0T 的 78%。

1.1.2　弥散张量成像(diffusion tensor imaging,

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DTI) 评估白质微结构完整性对于诊断神经系统疾病及预测预后至关重要。DTI 矩阵参数、尤其各向异性分数(fractional anisotropy, FA)和轴向扩散(axial diffusivity, AD)值是评估白质纤维束结构的关键指标。7.0T DTI 以高 b 值(b=2 000 s/mm^2)[4]有效抑制部分容积效应和脑脊液干扰,可显著提升图像 SNR 和测量参数的精确度。以 3.0T 及 7.0T DTI 测量健康人颈椎脊髓 FA 值的误差分别为 12%及 5%[5],表明 7.0T 技术可极大提高追踪白质纤维束的精确度和可靠性,为精准量化白质微结构奠定基础。

DTI 参数对于预测预后亦具有重要价值。CHERNYSH 等[6]针对脊髓型颈椎病(cervical spondylotic myelopathy, CSM)的研究结果显示,颈椎术前径向扩散(radial diffusivity, RD)值与术后 1 年日本骨科协会评分改善程度呈显著负相关($r=-0.82$, $P=0.003$);RD 值可作为预测手术疗效及神经功能恢复潜力的敏感指标,该值升高提示髓鞘受损。NISCHAL 等[7]亦发现 DTI 矩阵参数与 CSM 严重程度显著相关,进一步证实其作为监测疾病标志物的价值。采用 7.0T DTI 能更精准地量化 FA、AD 及 RD 等参数,提高评估白质准确性,更好地预测预后[8]。

1.2 功能 MRI(functional MRI, fMRI)

1.2.1 静息态 fMRI 7.0T 静息态 fMRI 有助于揭示脊髓神经环路异常(如慢性疼痛)。既往研究[9]纳入慢性神经病理性疼痛患者与健康对照者,采用 7.0T fMRI 行全脊髓静息态扫描,发现病变组脊髓-脑干默认模式功能网络连接较对照组增强约 1.8 倍($P<0.01$)。由此揭示了慢性疼痛状态下不仅存在脊髓水平自发神经活动异常,还可见其与脑干等上位调控脑区的信息整合失调,为理解疼痛中枢敏化及下行抑制控制功能受损提供了直接影像学证据。

1.2.2 任务态 fMRI 7.0T 任务态 fMRI 具有更为直观的敏感性优势,不仅有助于捕获脊髓微弱血氧水平依赖(blood oxygenation level dependent, BOLD)信号响应,还为动态观测肌萎缩侧索硬化(amyotrophic lateral sclerosis, ALS)等运动神经元疾病进展中的前角细胞失代偿变化提供了可能,可敏感捕获刺激任务范式下脊髓神经活动的微弱 BOLD 信号响应[10]、记录手指运动范式激活的 C6~C8 颈髓腹角运动神经元信号变化[11]。

1.3 运动校正技术 脊髓、特别是胸髓段 MR 成像易受呼吸及自主神经活动等生理运动伪影干扰而致图像模糊、显示解剖结构扭曲,严重影响诊断准确性。传统技术如呼吸门控与导航回波可有效地将图像配准误差控制在 0.5 mm 以内[12],但将延长扫描时间,且对非周期性运动(如吞咽、不自主抖动)的校正效果有限。近年来,深度学习技术大幅推进了运动校正的效能边界[13]。MARUYAMA 等[2]提出的伪影估计网络引入批量归一化和 dropout 层,显著提升了校正 MRI 运动伪影的稳定性及泛化能力;进一步研究[14]表明,利用此类网络模型可在显著提升图像质量(如峰值 SNR)的同时有效缩短扫描时间。

2 7.0T MRI 用于脊柱脊髓疾病

2.1 脊柱退行性疾病

2.1.1 椎间盘退变 7.0T MR 脊柱成像能清晰显示微小解剖结构及其病理变化如神经根鞘、韧带微撕裂及椎体终板炎等[15]。在椎间盘退变早期,利用 7.0T MRI 能敏感地检测髓核内水分丢失及纤维环微小裂隙,为研究椎间盘退变机制及早期干预提供了重要依据[16-18]。针对椎间盘退变致椎管狭窄,7.0T MRI 能精准测量椎管横截面积及脊髓受压程度等参数[6];尤其对于腰椎管狭窄,7.0T MRI 可清晰显示马尾神经受压以指导临床制定手术方案[7,15,19]。

2.1.2 ALS ALS 是致命性神经系统疾病,以皮质脊髓束及运动皮层上下运动神经元进行性退变为主要特征。在微观结构层面,ALS 患者皮质脊髓束 FA 值显著降低,提示存在轴突变性和脱髓鞘,且 FA 值降低与疾病进展呈显著负相关($r=-0.76$),表明 FA 不仅能反映结构损伤程度,还可用于评估疾病侵袭性[20];而利用 7.0T MRI 或能更精准地测量 FA 值。近年出现的多壳扩散成像、神经突方向离散度和密度成像等新技术为进一步精确揭示白质微环境变化提供了重要依据[8,21]。

2.1.3 脊髓小脑性共济失调(spinocerebellar ataxia, SCA) SCA 是常染色体显性遗传性神经退行性疾病,表现为小脑、脑干和脊髓神经元选择性丢失[22]。7.0T MRI 可清晰区分小脑皮层不同层次(如颗粒层和分子层)及深部核团(如齿状核)微观结构变化[23],甚至能显示早期铁沉积和神经炎症等顺磁性物质异常分布,从而为理解 SCA 不同基因型如何影响特定细胞类型易损性提供关键依据[24-25]。

2.2 脊髓疾病

2.2.1 急性脊髓炎 7.0T MRI 还可清晰区分脊髓细微解剖结构,特别是灰、白质。针对急性脊髓炎的研究[26-27]结果显示,7.0T MRI 可显示病变区域脊髓肿胀及 T2 高信号炎症区域,有助于动态观察炎症范围和信号强度变化、客观评估抗炎治疗效果。

2.2.2　MS　MS 是以中枢神经系统白质炎性脱髓鞘病变为主要特点的自身免疫性疾病[24]。多项研究[28-31]表明，7.0T MRI 不仅能识别传统场强下无法检测到的 MS 软脑膜下病灶和弥漫性白质损伤，还能借助定量磁化率图和相位成像在体分析病灶内铁沉积、微量出血及小胶质细胞激活等，从而定量评估脱髓鞘、髓鞘再生、轴突丢失、神经胶质增生和脊髓水肿等。一项纳入 126 例 MS 患者的研究[32]结果显示，7.0T MRI 检出皮质病变数目是 3.0T MRI 的 2.3 倍。相比 3.0T，以 7.0T MRI 测量 MS 患者海马区体积的精度提升约 30%，可显著提高评估灰质萎缩的敏感性[33-34]。基于 7.0T MR T2WI 还可评估 MS 所致软脑膜炎症，其软脑膜强化程度与残障风险呈显著正相关（$r=0.67$）[35]。

2.2.3　脊髓损伤　7.0T MRI 可清晰显示轴突损伤、再生及胶质瘢痕形成等脊髓细微病理变化。在脊髓损伤急性期（72 h 内），以脊髓 FA 值<0.4 预测损伤后 1 年美国脊髓损伤学会运动评分的敏感度、特异度及曲线下面积（area under the curve，AUC）分别为 88%、93%及 0.91[36-37]；而对慢性期脊髓损伤，利用 7.0T 磁化转移成像能精准量化瘢痕范围、指导神经再生治疗，DTI 则可清晰显示损伤部位白质纤维束中断；联合 T2WI 能综合评估轴突微观结构完整性，为选择神经康复治疗时机和调整方案提供依据[36,38-39]。

2.2.4　肿瘤及血管畸形　7.0T 化学交换饱和转移成像可清晰显示室管膜瘤边界，有效区分肿瘤浸润区与水肿带（AUC=0.93）；还能预测胶质瘤异柠檬酸脱氢酶突变（特异度 89%）[40]。7.0T 时间分辨 MR 血管成像可显示血管病变如动静脉畸形的细节，甚至检出直径<200 μm 的滋养动脉[41-42]。

3　挑战与展望

当前 7.0T MRI 的临床应用仍面临诸多挑战，包括脊柱线圈覆盖范围有限使得腰椎成像效果显著低于颈胸段[43]、射频不均匀造成图像伪影、不同中心扫描协议差异导致参数测值存在误差[44-45]，以及设备昂贵、扫描时间长及患者舒适度低等。近年来，技术创新持续推动 7.0T MRI 发展：7.0T PET/MRI 融合可将高分辨率解剖与代谢功能信息相结合，降低测量肿瘤代谢体积误差；借助小型化磁体设计，便携式 7.0T 系统（如 Magnetom Terra）有望广泛用于临床（包括术中实时成像）[46]。未来可通过优化射频线圈设计、改进序列参数，结合人工智能进一步推动 7.0T MRI 的临床应用。

4　小结

7.0T MRI 已在诊断脊柱脊髓疾病、评估疗效及相关基础研究等方面展现出巨大潜力。随着技术不断发展，7.0T MRI 有望广泛用于临床，成为评估脊柱脊髓疾病的重要手段。

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