·综述·

7.0T MRI在关节软骨中的研究进展*
Research Progress of 7.0T MRI in Articular Cartilage*

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关节软骨损伤导致残疾、持续性疼痛和社会经济负担[1-2]。关节软骨损伤的主要特征是渐进的、不可逆的软骨变性，包括胶原网络的破坏、蛋白聚糖的消耗和水含量的改变，从而引发结构改变。7.0T MRI已应用于许多肌肉骨骼领域，特别是用于软骨的研究。有研究对比了3.0T和7.0T膝关节二维和三维常规MRI序列的成像效果，在相同的扫描时间下，7.0T MRI的空间分辨率较3.0T可提高1.3~3.9倍[3]。本文综述了7.0T MRI技术在关节软骨损伤研究领域中的最新进展。

1 7.0T MRI的功能成像

1.1 T2 mapping T2 mapping技术对胶原基质的整体性、糖胺聚糖(glycosaminoglycan, GAG)含量以及水分子水合作用的变化表现出高度敏感性[4]。在骨关节炎的早期病理进程中，胶原基质降解与糖胺聚糖缺失是关键特征，因此，众多临床研究采纳T2 mapping作为评估骨关节炎风险的一个重要指标[5]。Chang等人的一项研究观察了手术修复的膝关节软骨与健康对照，Domayer等人的一项研究比较了手术后踝关节软骨与健康对照，两项实验均表明能够在7.0T MRI下区分软骨修复组织与健康软骨，证明其能够检测关节软骨损伤后的胶原蛋白组成[6-7]。在超高场MR扫描仪上，研究者可以使用三重回波稳态(TESS)序列替代传统的多回波自旋回波序列的方案，其提供三维覆盖、更低的特定吸收率需求和更短的测量时间[8]。三重回波稳态(TESS)技术是一种具有低射频能力特定吸收率(Specific Absorption Rate, SAR)、良好空间覆盖和对B0和B1不均匀性不敏感的有效T2-mapping技术。另外，使用灰度共生矩阵(GLCM)特征的定量MR图的纹理分析，提供了关于胶原组织的附加信息，并且可以用于确定软骨状态[9]。

1.2 T1ρ mapping T1ρ(或T1rho)的定义就是旋转坐标系中，在水平方向特定的射频脉冲激发下表现的自旋-晶格弛豫，T1ρ对于细胞外水和其他大分子之间的化学交换相关的低频相互作用敏感，特别是探测水与糖胺聚糖之间的相互作用[10-12]。因此，它对软骨基质中糖胺聚糖区域的变化表现出高度的敏感性，并已有实验验证在膝关节和髋关节中，7.0T MRI对于糖胺聚糖区域的变化更加敏感[13-14]。即使在T2 mapping中未见变化，T1ρ技术仍能探测到糖胺聚糖含量的轻微降低，从而识别老化软骨中的退行性变化。Singh[15]等人在7.0T下获得了膝关节软骨的高SNR和高分辨率3D T1ρmapping图像，平面内分辨率为0.2mm²，与3.0T相比，在7.0T下研究人员在减少四倍的扫描时间内达到了相同的分辨率。

1.3 化学交换饱和转移成像 化学交换饱和转移(chemical exchange saturation transfer, CEST)根据其不稳定羟基(-OH)与本体水的化学交换直接定量糖胺聚糖含量[16]。CEST通过使用一系列偏共振饱和脉冲进行预饱和，然后观察水信号强度的降低，这种信号强度的降低与局部大分子含量成比例。7.0T MRI改善了CEST性能，因为SNR增加和共振频率间隙增加，羟基糖胺聚糖和水质子之间的饱和度更具选择性[17-19]。使用CEST对关节软骨中糖胺聚糖进行定量，对于检查软骨变性并诊断早期骨关节炎具有很高的潜力[20]。在7.0T下进行首次CEST应用，用于术后膝关节软骨评价[21]。一项3.0T与7.0T比较研究表明，需要7.0T MRI准确估计糖胺聚糖，以避免在3.0T下观察到的直接饱和效应和快速交换率[22]。然而，在以前的应用中，CEST数据主要是在2D中采集的，因为3D序列非常耗时。有研究提供了一种快速的3D CEST序列，具有完全软骨覆盖，可以量化健康志愿者和患者中的糖胺聚糖，数据可以在7分钟内获得，并显示出稳定性、可重复性和临床适用性[23]。

1.4 钠成像 钠磁共振成像(23Na-MRI)是一种先进的成像方式，可提供非侵入性代谢成像，用于多种疾病的早期诊断和疗效评价。在关节软骨中，带负电荷的糖胺聚糖被带正电荷的钠离子抵消，因此，钠浓度可用作糖胺聚糖量的间接指标，而糖胺聚糖量又可使用钠成像进行无创评估[24-25]。在退变软骨中，糖胺聚糖的丢失会导致钠含量的相应下降[26]。钠在健康软骨中的浓度为250~350 mM，在骨关节炎软骨中的浓度开始低于250 mM[27]。超高场核磁共振中钠成像，在骨关节炎及关节软骨修复的研究中，被证实可用于糖胺聚糖含量的测定[28]。Wang[29]等人首先在7.0T条件下使用3D GRE序列和径向k空间采集,在不到15分钟的时间内获得了整个膝关节的3D钠图像。他们观察到与健康受试者相比，骨关节炎患者的钠浓度显著降低。最近，通过引入压缩感知技术，膝关节7.0T MRI钠成像的扫描时间缩短了两倍，而对于骨关节炎早期诊断的准确性没有损失。Chang[30]等人比较了11例患者在接受几种不同的软骨修复手术后，在有和无液体抑制的情况下获得的钠成像结果。研究结果表明，与标准序列相比，液体抑制钠成像更加稳定，以及移植组织邻近软骨的钠浓度明显低于健康软骨。最近，Gast[31]等人开发了一种基于钠成像的方法，用于在7.0T下进行局部B0匀场，并表明使用这种方法可以将外部场强不均匀性降低77%。关节软骨的钠磁共振成像是具有挑战性的，其准确性受到几个因素的限制，例如由相对低的空间分辨率引起的部分容积效应，由于TE不够短而导致的T2短衰减的信号损失，以及由于读出期间信号快速衰减而导致的T2模糊[32]。

1.5 磁共振延迟增强成像 延迟钆增强软骨磁共振成像(delayed gadolinium enhanced MRI of cartilage, dGEMRIC)技术可进行骨关节炎早期识别和严重程度预测[33]。dGEMRIC可通过使用带负电荷的造影剂二乙烯三胺五乙酸钆(Gd-DTPA)来反映软骨中带负电荷的糖胺聚糖分布，从而评估关节中的软骨[34-35]。dGEMRIC通

过测量造影后T1弛豫时间(称为dGEMRIC指数)来定量评估软骨退化[36]。在体内、体外和离体组织学研究中，较低的dGEMRIC指数与更严重的骨关节炎相关。Welsch[37]等人证明了在健康志愿者静脉注射Gd-DTPA，进行膝关节中7.0T的延迟钆增强软骨MRI的体内可行性。T1 mapping是dGEMRIC技术的核心组成部分，有研究提出了几种方法。标准方法是2D反演恢复(IR)技术，但在过去的几年中，诸如可变翻转角(VFA)和Look-Locker (LL)技术等3D方法也越来越多地投入使用。当移动到更高的场强时，预计精确的T1 mapping会遇到一些挑战。首先，较长的T1值可能需要较长的反转和重复时间，这增加了采集时间。其次，与临床场强相比，超高场强下的B1场可能更不均匀。这可能会影响IR和LL实验的反转脉冲的质量，但也可能使VFA和LL技术需要B1校正方法[38]。对于这两种3D方法，B1校正对于准确的T1 mapping是至关重要的，以及对于LL和IR，在7.0T时B0匀场是至关重要的[39]。

2 7.0T MRI对关节软骨损伤诊断的优势和技术挑战

7.0T MRI无需使用对比剂，即可对解剖细节和细微病变进行观察，在获得高质量图像的同时实现更快的扫描速度和更高的空间分辨率。而且体素减小有助于减低部分容积效应，对软骨厚度和体积的测量更加精确[40]。目前，在7.0T MRI中证实了关节软骨高分辨率成像的可行性的是膝关节、髋关节、腕关节及踝关节等[41-45]。FRIEBE[46]等在3.0T及7.0T质子密度加权成像序列研究中证实了在相同的采集时间下，7.0T采集到的软骨和半月板损伤图像的分辨率及诊断准确性均优于3.0T。

7.0T MRI所需的B1场与B0场强度成二次方，与较低场强相比，这需要增加B1功率以实现相似的翻转角，但这影响到了比吸收率(Specific Absorption Rate, SAR)[47]。从3.0T到7.0T，组织中的射频脉冲波长从约35 cm降低到约15 cm，导致射频脉冲穿透组织的能力降低，从而导致整个样本的翻转角变化。此外，在较高的场强中，组织的弛豫值发生变化。一般来说，T1值增加，T2值增加，T2*值由于敏感性增加而降低[48-49]。7.0T MRI所独有的物理特性引起了技术挑战，这些挑战包括了化学位移伪影的加剧、磁场均匀性的下降、磁化率效应的增强以及潜在安全风险的上升(具体涉及磁性物体意外进入扫描区域的风险、植入物安全问题、以及组织加热等不良反应)等[50-51]。在采用7.0T MRI技术时，医务人员还需审慎考量强磁场对人体的潜在影响。根据当前美国食品药品监督管理局(FDA)的安全指导原则，磁场强度低于8.0T时，对人体不构成长期健康威胁，尽管个别个体可能经历短暂性眩晕、极少数人报告口腔金属味觉异常或视觉闪烁现象，但基本上是安全的[52]。

在超高场强下，MRI通过增加接收带宽、视角倾斜以及用于金属伪影校正的切片编码，来减少存在金属时的植入物周围信号空隙和几何失真。金属伪影的程度与场强成正比[53]。因此，7.0T MRI的金属伪影技术将有助于获得患者的均匀信号强度[54]。通常，MRI需要先进的加速技术来实现临床可行的扫描时间，例如压缩感知。虽然在从1.5T到3.0T的过渡中，通常使用更高的场强来加速图像采集，但与3.0T MRI相比，扫描时间的减少在当前的7.0T MRI中没有很高的优先级[55]。在超高场强的临床方案优化过程中，可能会出现脂肪饱和度低、大量伪像和特定吸收率增加的情况[56]。然而，随着专用的多通道收发线圈的引入。将克服这些技术限制[57]。

3 总　结

7.0T MRI的高分辨率和高信噪比能够精确展示关节软骨的微细结构，有助于早期病变的检测和诊断。但是，7.0T MRI作为诊断临床成像工具被更广泛接受需要满足的一些要求，比如减轻7.0T MRI的安全问题，定制脉冲序列优化，开发新的线圈和成像硬件，以及克服7.0T MRI成像的挑战。不可否认的是，7.0T MRI在关节软骨成像中具有优秀的使用价值和巨大的临床应用前景。

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