·临床研究·

小视野 DWI 在中轴型脊柱关节炎定量评估中的价值

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摘　要：【目的】探讨小视野弥散加权成像（r-FOV DWI）在中轴型脊柱关节炎定量评估中的应用价值。【方法】前瞻性收集 2019 年 11 月至 2021 年 11 月间因慢性腰痛、临床怀疑中轴型脊柱关节炎同时行小视野和全视野 DWI 成像者 112 例。首先，2 名研究者对 DWI 图像质量进行主、客观评价，主观评估包括图像解剖细节、变形、伪影、整体图像质量的评分，客观评估包括图像信噪比和对比噪声比。然后，相同 2 名研究者分别在小视野和全视野 DWI 上测量 3 组（活动组、非活动组和对照组）的表观扩散系数（ADC）值，评价观察者间的测量一致性，比较 ADC 值有无差异。绘制两种技术 ADC 值受试者工作特征曲线并比较曲线下面积（AUC）。【结果】最终纳入 102 例，根据国际脊柱关节炎协会（ASAS）MRI 工作组诊断标准分为 3 组，其中活动组 32 例、非活动组 29 例、对照组 41 例。小视野 DWI 图像的主观评分高于全视野 DWI［4（3~4）*vs.* 3（3~3），$P<0.05$］；小视野 DWI 图像的客观评分高于全视野 DWI 信噪比：6.58（5.05~10.38）*vs.* 4.46（2.37~10.04）对比噪声比：2.04（-1.14~8.29）*vs.* 0.97（-8.19~7.12）；$P<0.05$）。两名观察者测量的组间一致性 0.60~0.74（ICC 相关系数）；活动组、非活动组和对照组的 ADC 值均具有显著差异（$P<0.05$），小视野 DWI 测量的 ADC 值高于全视野 DWI。非活动组 vs. 对照组 AUC 结果显示，全视野 DWI 在非活动组 *vs.* 对照组中优于小视野 DWI，其他组别（病变组 *vs.* 对照组、活动组 *vs.* 非活动组）两种 DWI 技术没有统计学差异（$P<0.05$）。【结论】小视野 DWI 可用于中轴型脊柱关节炎的定量评估，且其图像主观评分和信噪比较全视野 DWI 高。

关键词：小视野弥散加权成像；中轴型脊柱关节炎；磁共振成像；表观扩散系数
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Value of Reduced Field-of-view DWI in Quantitative Assessment of Axial Spondyloarthritis

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Abstract：【Objective】To investigate the value of reduced field-of-view DWI（r-FOV DWI）in quantitative assessment of axial spondyloarthritis.【Methods】A total of 112 patients with chronic back pain or suspected axial spondyloarthritis receiving full field-of-view DWI（f-FOV DWI）and reduced field-of-view DWI（r-FOV DWI）from December 2019 to December 2021 were enrolled. Next，subjective image quality assessment（anatomical detail，artifacts，distortion，overall image quality）and objective image quality assessment including（signal to noise ratio and contrast to noise ratio）were conducted by two experienced radiologists. In addition，the Apparent Diffusion Coefficient（ADC）values of three groups（active group，inactive group，and control group）on the two DWI sequences were measured by the two radiologists，respectively. Finally，the consistency of measurement between the two researchers was evaluated and the differences in ADC

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values was compared.【Results】102 patients were included and were divided into three groups, including the active group (n=32), inactive group (n=29), and control group (n=41) according to ASAS diagnostic criteria. All subjective and objective image quality metrics were rated in favor of r-FOV DWI images compared with f-FOV DWI images [overall image quality: DWI 4(3~4) *vs*. 3(3~3) and SNR: 6.58(5.05~10.38) *vs*. 4.46(2.37~10.04), CNR: 2.04(-1.14~8.29) *vs*. 0.97(-8.19~7.12); $P<0.05$]. Inter-rater consistency of the two researchers were 0.60~0.74. According to the AUC curve, group inactive *vs*. control showed r-FOV DWI was better than f-FOV DWI. In other groups (lesion *vs*. control, active *vs*. inactive), there were no differences between both sequences ($P<0.05$).【Conclusion】The subjective image quality score and signal to noise ratio of r-FOV DWI were higher than those of f-FOV DWI, which could be used for quantitative assessment of axial spondyloarthritis.

Key words: reduced field-of-view DWI; ankylosing spondylitis; magnetic resonance imaging; apparent diffusion coefficient

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中轴型脊柱关节炎(axial spondyloarthritis, axSpA)是一种慢性、炎症性疾病，多发生于青壮年，发病率近年来逐年上升，主要表现为晨僵和腰背痛，中晚期可伴有脊柱强直及严重活动受限，致残率高，有“不死的癌症”之称。axSpA的早期、精准定量评估对于治疗方案的选择和疗效评价具有非常重要的指导价值，然而目前临床上axSpA多为定性诊断和半定量评估，缺乏精准定量方法[1-3]。磁共振成像(magnetic resonance imaging, MRI)能检测axSpA的早期活动性病变，是临床诊断重要的检查手段[2]。弥散加权成像(diffusion-weighted imaging, DWI)主要反映水分子的布朗运动，研究表明，DWI序列的表观扩散系数(apparent diffusion coefficient, ADC)值提供的定量资料可用于强直性脊柱炎活动性的评估[4]。目前临床上应用的全视野弥散加权成像(full field-of-view diffusion-weighted imaging, f-FOV DWI)是单次激发平面回波成像(single shot echo planar imaging, SS-EPI)，易受非共振因素影响，导致图像出现模糊、失真、磁敏感伪影等情况，影响临床观察及诊断。小视野弥散加权成像(reduced field-of-view DWI, r-FOV DWI)，通过减少相位编码方向的FOV，从而减少SS-EPI所需的读出持续时间[5]，同时采用二维空间选择性激发脉冲和180°重聚焦脉冲，通过减少K空间填充相位编码方向所需要的时间，能显著减少非共振引起的伪影并减轻图像的模糊[6]。r-FOV DWI序列显示胰腺、直肠、胆囊等器官病变优于f-FOV DWI序列[6-7]，但未发现应用于骶髂关节的相关研究。本研究通过比较f-FOV DWI与r-FOV DWI在SpA患者骶髂关节显示及病变评估情况，探讨小视野DWI在axSpA中的应用价值。

1　材料与方法

1.1　一般资料

搜集2019年11月至2021年11月，在我院接受骶髂关节MRI检查(包括f-FOV DWI和r-FOV DWI序列)。纳入标准：40岁前慢性腰痛病史，临床疑似axSpA的患者[8]。排除标准：致密性骨炎和骶髂关节骨关节炎、骨折、感染性骶髂关节炎、骨转移或原发性骨肿瘤、幽闭恐惧症等磁共振禁忌[9]。本研究经院伦理委员会批准[编号：中大五院(2019)伦字第(K160-1)号]，检查前患者均签署知情同意书。

1.2　仪器与方法

使用GE超导型MR扫描仪(signa pioneer 3.0 T)，16通道腹部相控阵线圈。受检者取仰卧位，头先进，平行于S1-S3背侧连线扫描斜冠状位骶髂关节MRI。扫描参数：T1WI序列，TR/TE 602 ms/15.2~20.3 ms，扫描时间2 min 32 s；短时翻转恢复(short TI inversion recovery, STIR)序列，TR/TE 5 856 ms/28 ms，扫描时间4 min 24 s。常规序列其余参数均一致：矩阵320×256，FOV 240 mm×240 mm，层厚/层间距4 mm/1 mm；f-FOV DWI序列，TR/TE 4 000 ms/77ms，矩阵128×128，FOV 240 mm×240 mm，层厚/层间距3 mm/1 mm，扫描时间7 min 38 s；r-FOV DWI序列，TR/TE 4 684 ms/71 ms，矩阵128×64，FOV 200 mm×100 mm，层厚/层间距3 mm/1

mm,扫描时间3 min 54 s。

1.3 分组标准

两名研究者(分别具有6年、3年骨肌系统MR诊断经验)在对患者临床信息不知情的情况下,通过患者常规序列图像观察有无活动性病变,意见不一致则以第三名医师(20年骨肌系统磁共振诊断经验)意见为准。具体规则如下:接受骶髂关节MRI检查、不符合ASAS工作组SpA诊断标准,且骶髂关节MRI无任何活动性或结构性改变的受检归为对照组。SpA的诊断标准为:慢性腰痛超过3个月,通过X线摄影或MRI检查存在骶髂关节炎加上至少一个SpA特征,或存在HLA-B27阳性加上至少两个SpA特征。诊断为SpA的病例中,根据是否存在活动性病变,将axSpA患者分为活动组和非活动组。活动性病变定义为:对于单个骨髓水肿,应至少在两个连续层面观察到;如在单个层面能观察到多个骨髓水肿,则只需一个层面[8,10]。

1.4 图像分析

1.4.1 图像质量的主观评估 所有图像均在GE AW 4.7工作站分析处理。两名观察者,分别观察f-FOV DWI和r-FOV DWI图像,对图像按照李斯特5分法进行评分,具体评分标准见参考文献[11]。

1.4.2 图像质量的客观评估:信噪比和对比噪声比 两名观察者在f-FOV DWI和r-FOV DWI图像分别测量骨髓和腰大肌的信号值,计算相对信噪比(signal-to-noise ratio,SNR),计算算式:$SNR=SI_{骨髓}/SD_{肌肉}$;对比度噪声比(contrast-to-noise ratio,CNR),计算算式:$CNR=(SI_{骨髓}-SI_{肌肉})/(SD_{骨髓}-SD_{肌肉})$,其中,$SI_{骨髓}$为骨髓的信号值,$SD_{肌肉}$为肌肉信号值的标准差[3]。

1.4.3 DWI用于中轴型脊柱关节炎的定量活动性评估 利用f-FOV DWI和r-FOV DWI序列,分别测量活动组、非活动组和对照组3组的ADC值,具体方法如下:在GE AW 4.7工作站通过f-FOV DWI和r-FOV DWI序列的两个b值(0 s/mm^{2}和800 s/mm^2)分别自动生成ADC图,两名观察者在不知道分组结果的情况下,分别测量两个序列的ADC值,在骨髓水肿处测量ADC值。若存在多个病灶,则有几个病灶测量几个,最后取平均值。对于肉眼观察不到明显信号异常的病例,在每侧骶、髂侧各分上、中、下三区,每个病例共12区,取平均值。勾画ROI时避开血管、骨皮质、囊肿及骨质硬化区域[12]。

1.4.4 ADC值诊断效能评价 以分组结果,即临床诊断结合MR常规序列(T1WI、STIR)为金标准,使用ROC曲线(receiver operating characteristic curve,受试者操作特性曲线)比较分析两种技术的诊断效能。病变组(活动组和非活动组的总和)vs.对照组中病变组定义为阳性、活动组vs.非活动组和活动组vs.对照组中活动组定义为阳性、非活动组vs.对照组中非活动组定义为阳性。

1.5 统计学分析

所有数据采用SPSS 24.0和MedCalc软件进行统计分析,使用Wilcoxon秩和检验比较两种技术的主观评分差异,使用Wilcoxon秩和检验比较两种技术的主观评分及SNR,$P<0.05$有统计学差异。使用组内相关系数(intraclass correlation coefficient,ICC)分析测量值的观察者测量ADC值的组间一致性(<0.40,差;0.40~0.59,一般;0.60~0.74,良好;≥0.75,优秀),使用Kruskal-Wallis检验比较两名观察者测量的活动组、非活动组和对照组ADC值,并两两比较。使用ROC曲线比较分析两种技术的诊断效能,并计算其ROC曲线下面积(area under roc curve,AUC)、截断值、灵敏度和特异度。$P<0.05$有统计学差异。

2 结 果

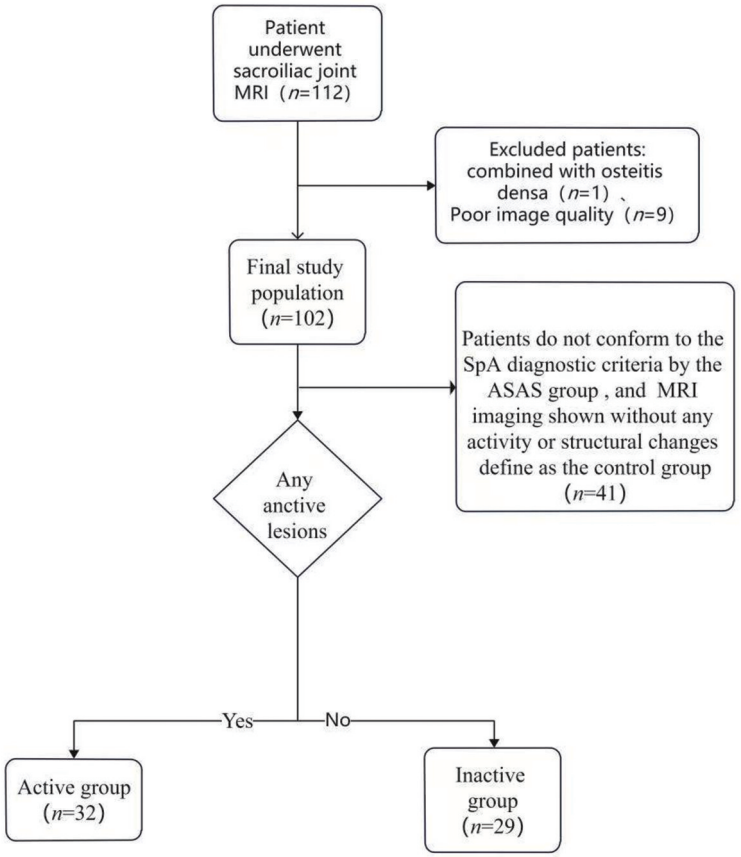
本研究共收集受检者112名,剔除合并致密性骨炎1名、伪影严重病例9名,最终纳入102名,其中活动组32名、非活动组29名、对照组41名。平均年龄31.4±8.2(19~50),其中男74名,女28名(图1)。

2.1 图像分析结果

三组病例在f-FOV DWI和r-FOV DWI序列的显示情况见图2~4。两名观察者图像主观及客观评分结果如表1所示,一致性均为优秀(ICC>0.75;表2),除伪影评分情况没有统计学差异外,r-FOV DWI序列均优于f-FOV DWI序列($P<0.05$)。

2.2 ADC值测量结果

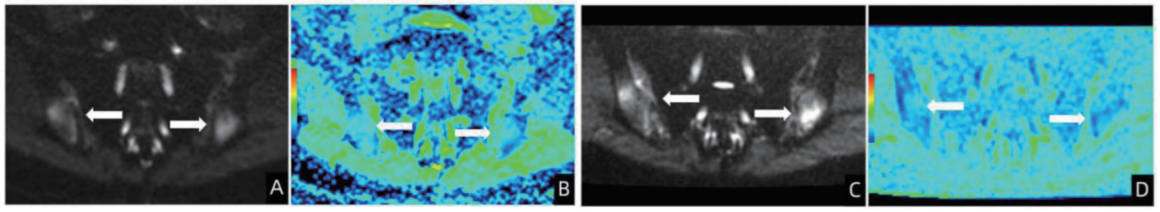
两名观察者的ADC测量值ICC组内一致性系数结果为一般(0.60-0.74;表3)。将两名观察者测得的ADC值取平均值,采用Kruskal-Wallis H检验比较测量结果,根据直方图判断各组中ADC值分布的形状不一致。各组ADC值的分布不全相同,差异具有统计学意义(图5)。观察者f-FOV DWI



112 patients were screened and 10 were not included in the study due to combined with osteitis densa (n=1), and with poor image quality (n=9).

图1　研究流程图

Fig. 1　The flow chart



A-26-year old male patient with duration of 3 years lumbar and left hip pain, worsening for a week. Conventional MRI sequence shown multiple patchy high signal under the bilateral sacroiliac joint surface, the boundary was not clear, in this study was classified as active group. Figure A and B were f-FOV DWI and f-FOV DWI ADC maps (b-value=0, 800 s/mm^2). Figure C and D were r-FOV DWI and ADC r-FOV DWI maps (b-value=0, 800 s/mm^2). White arrows shown bone marrow edema, clear boundary was shown in figure C and it was green in figure B and D.

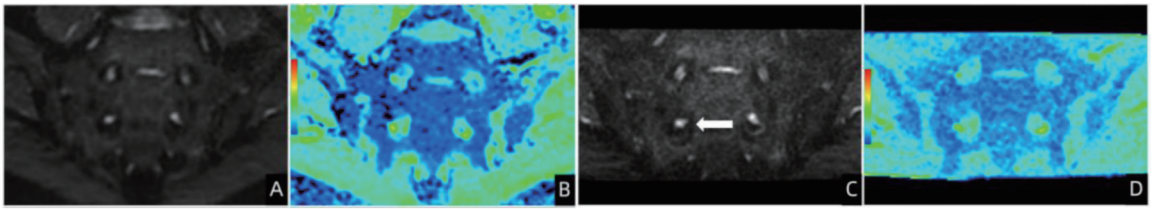
图2　活动组显示情况

Fig. 2　Images of active group

序列三组ADC值：(H=174.650，P<0.001)。活动组ADC值平均秩次为1.11×10^{-3}mm^2/s(n=64)，非活动组ADC值平均秩次为0.45×10^{-3}mm^2/s(n=58)，对照组ADC值平均秩次为0.25×10^{-3}mm^2/s(n=82)。观察者r-FOV DWI序列三组ADC值：(H= 149.282，P< 0.001)。活动组ADC值平均秩次为1.40×10^{-3}mm^2/s(n=64)，非活动组ADC值平均秩次为1.00×10^{-3}mm^2/s(n=58)，对照组ADC值平均秩次为0.83×10^{-3}mm^2/s(n=82)。采用Bonferroni法校正显著性水平的事后两两比较发现，所有ADC值的分布在各组的差异均有统计学意义(P <0.05)。

2.3　诊断效能

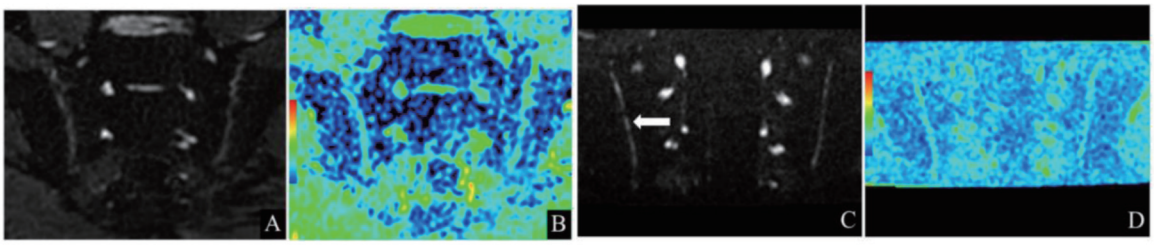
三组病例诊断效能见表4和图6，病变组(活动组与非活动组)*vs*.对照组f-FOV DWI和r-FOV



A-36-year-old male patient with duration of 10 years Lumbar and sacral pain, bluring edges were illustrated in bilateral sacroiliac joints. Conventional MRI sequence shown the subchondral bone saw no obvious edema, hardening or lipid deposition, in this study was classified as inactive group . Figure A and B were f-FOV DWI and f-FOV DWI ADC maps (b-value=0, 800 s/mm^2).Figure C and D were r-FOV DWI and ADC r-FOV DWI maps (b-value=0, 800 s/mm^2). White arrows shown clearly sacral pore structure and the boundaries was clear.

图3 非活动组显示情况

Fig. 3 Images of inactive group



A-44-year-old male patient with duration of 3 years Lumbar and sacral pain. Conventional MRI sequence bilateral sacroiliac joints shown no obvious abnormity regular sequences, in this study was classified as control group. Figure A and B were f-FOV DWI and f-FOV DWI ADC maps (b-value=0, 800 s/mm^2).Figure C and D were r-FOV DWI and ADC r-FOV DWI maps (b-value=0, 800 s/mm^2). White arrows shown clearly Joint clearance.

图4 对照组显示情况

Fig. 4 Images of control group

表1 主观及客观评分结果

Table 1 Subjective and objective scoring results [$M(P_{25}\sim P_{75})$]

Items	f-FOV DWI	r-FOV DWI	Z	P
SNR	4.46(2.37~10.04)	6.58(5.05~10.38)	-0.439	<0.001
CNR	0.97(-8.19~7.12)	2.04(-1.14~8.29)	-2.341	0.019
Anatomical Detail	3(3~3)	4(4~4)	-10.643	<0.001
Artifacts	4(4~4)	4(4~4)	-0.604	<0.546
Distortion	3(3~4)	3(3~4)	-0.169	0.866
Overall image quality	3(3~3)	4(3~4)	-7.033	<0.001

n=204,Data in the table were averages of measurements taken by two observers.

DWI序列活动性检查的诊断效能差异无统计学意义(Z =1.399,P =0.161 8);活动组 *vs.* 非活动组诊断效能差异无统计学意义(Z =1.408,P =0.159 2);非活动组 *vs.* 对照组诊断效能差异有统计学意义(Z =3.704,P =0.000 2)。

3 讨 论

据我们充分调研文献所知,目前没有将r-FOV DWI应用于骶髂关节的研究报道。axSpA病程长、临床症状常缺失或不典型,其活动性病变通常最早发生在骶髂关节,骶髂关节X线摄影及CT检查一直是其重要的检出手段,随着磁共振技术日益发展,MRI在活动性病变的作用逐步显现[13]。2019年,ASAS MRI工作组更新了MRI上活动性骶髂关节炎的定义,其中列出了MRI检查的常规序列(T1加权和T2脂肪抑制序列),然而没有涉及定量序列[14]。我们之前的研究将集合序列定量技术(T1、

表2　主观及客观评分ICC一致性

Table 2　ICC consistency of subjective and objective scores

Items	f-FOV DWI	r-FOV DWI
SNR	0.832(0.694, 0.901)	0.873(0.780, 0.922)
CNR	0.792(0.706, 0.855)	0.762(0.667, 0.833)
Anatomical Detail	0.871(0.815, 0.911)	0.918(0.881, 0.944)
Artifacts	0.916(0.878, 0.942)	0.942(0.916, 0.962)
Distortion	0.898(0.853, 0.930)	0.911(0.872, 0.939)
Overall image quality	0.889(0.840, 0.924)	0.882(0.830, 0.918)

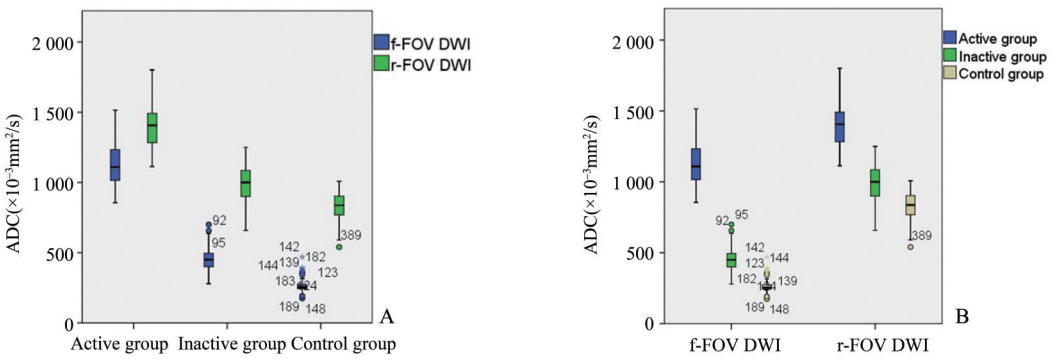
n=102，Data in parentheses were 95%CI(Confidence interval).

表3　两名观察者ADC值组间一致性结果

Table 3　Intergroup consistency of ADC values between two observers

Groups	f-FOV DWI	r-FOV DWI
Active group	0.748(0.544, 0.869)	0.746(0.541, 0.867)
Inactive group	0.706(0.462, 0.850)	0.730(0.501, 0.863)
Control group	0.689(0.436, 0.841)	0.727(0.542, 0.844)

n=102，Data in parentheses were 95%CI(Confidence interval).



Boxplot for the ADC values correlated with three groups indicates significant differences (P <0.05).

图5　两名观察者的ADC测量值对比图

Fig. 5　ADC measurements of two observers

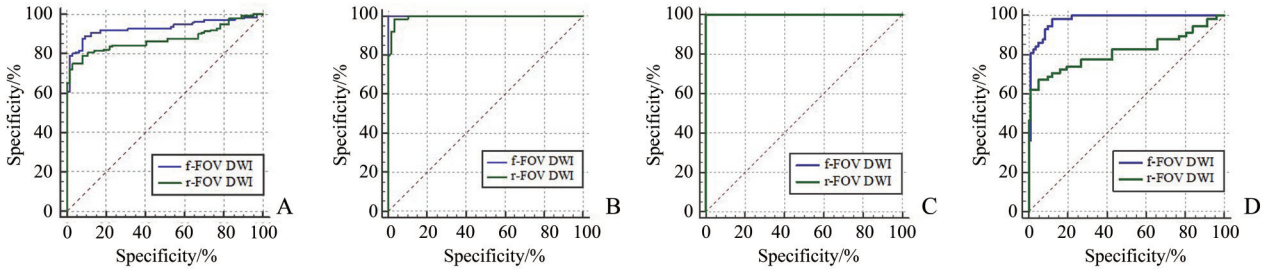
T2、PD定量值)应用于axSpA患者骶髂关节，结果显示其定量值能很好区分活动性和非活动性病变[15-16]。f-FOV DWI序列在EPI序列的180°脉冲前后各加入一个扩散敏感梯度脉冲，能显示出不同组织由于水分子扩散速度不同而导致的信号差异，得到的图像同时包含了组织间的T2弛豫对比信息和水分子扩散的对比信息[17]。Zhao等[4]将f-FOV DWI应用于强直性脊柱炎患者骶髂关节活动组、非活动组和对照组，结果显示，其ADC值能很好区分三组患者。r-FOV DWI序列采用特殊的2D空间选择性射频脉冲，其在层面选择和相位编码方向上都具有空间选择性，能单独调整每个射频脉冲以获得更为统一的反转角度，个体或容积特异性地修正射频磁场。同时，采用180°回聚脉冲技术取代了传统EPI序列中使用的层面选择性90°脉冲，能充分脂肪抑制并激发水信号，减少化学位移伪影，更能增加微小病变检出率[18]。本研究中，我们首次将f-FOV DWI和r-FOV DWI序列应用于axSpA患者骶髂关节，比较两个序列对病变的显示及定量值的差异。

表4 诊断效能

Table 4 Diagnostic efficiency

Items		Cut off($\times10^{-3}$)	Sensitivity/%	Specificity/%	AUC	95%CI	*P*
Lesion group *vs.* Control group	f-FOV DWI	0.39	90.98	98.78	0.989	0.964-0.998	<0.0001
	r-FOV DWI	0.99	81.97	98.78	0.913	0.865-0.947	<0.0001
Active group *vs.* Inactive group	f-FOV DWI	0.70	100	100	1.000	0.970-1.000	<0.0001
	r-FOV DWI	1.15	98.44	96.55	0.994	0.959-1.000	<0.0001
Active group *vs.* Control group	f-FOV DWI	0.47	100	100	1.000	0.975-1.000	<0.0001
	r-FOV DWI	1.01	100	100	1.000	0.975-1.000	<0.0001
Inactive group *vs.* Control group	f-FOV DWI	0.30	98.28	87.8	0.977	0.937-0.995	<0.0001
	r-FOV DWI	0.95	67.24	95.12	0.816	0.742-0.876	<0.0001

The lesion group was the sum of the active group and inactive group.



A: lesion group (the sum of the active group and inactive group) *vs.* control group; B: activity groups *vs.* the inactive group; C: activity group *vs.* control group; D: inactive group *vs.* control group.

图6 两种技术ADC值诊断效能ROC曲线分析

Fig. 6 Two kinds of ADC values in diagnosis efficiency ROC curve analysis

本研究主观评价结果显示,r-FOV DWI序列图像在解剖细节显示好、失真少,整体图像质量和SNR均优于f-FOV DWI序列,这与r-FOV DWI序列应用于胰腺[7]、直肠[6]、胆囊[19]等器官的研究结果相同。两组DWI图像CNR标准差较大,这可能由于采用相对对比噪声比计算所致。f-FOV DWI序列由于相位编码方向上K空间填充时间较长,易产生变形和磁敏感伪影,但在本研究中两组DWI图像变形项评分均较高,且变形和伪影评分没有统计学差异,可能由于其他研究均临近或属于空腔脏器,而骶髂关节属于骨关节,与空腔脏器或气体有一定距离,产生磁敏感伪影的概率较小,r-FOV DWI序列在这方面的优势没有显示出来。

两个序列的ADC值在活动组、非活动组和对照组均有统计学差异,两名观察者测量的ADC值组间一致性一般,可重复性一般。活动组由于发生血管源性水肿,细胞间液减少,细胞内水增多,导致局部扩散加强,表现为ADC值升高;非活动组ADC值高于对照组主要是由部分病例存在脂肪沉积,其T2弛豫时间较长所致[16]。本研究中,f-FOV DWI序列活动组ADC值为1.11×10^{-3} mm²/s,非活动组ADC值为0.45×10^{-3} mm²/s,对照组ADC值为0.25×10^{-3} mm²/s。比较之前f-FOV DWI序列在axSpA的ADC测量结果[4, 20-21],波动范围较大,对照组(0.23~0.38)$\times10^{-3}$ mm²/s、非活动组(0.41~0.9)$\times10^{-3}$ mm²/s、活动组(0.57~1.34)$\times10^{-3}$ mm²/s。Zhang[21]等认为由于EPI序列存在T2*模糊和伪影的增加可能会影响正常组织旁病变的ADC值,导致f-FOV DWI序列ADC值可信度较差。同组别f-FOV DWI序列ADC值与r-FOV DWI序列ADC值均有统计学差异,在之前对比f-FOV DWI序列与r-FOV DWI序列ADC值的研究中,部分显示有统计学差异[11, 22],部分则不存在统计学差异[6-7, 19]。分析原因,可能由于ADC值易受磁场强度[23]、扫描参数、b值、SNR等多

方面因素影响。Cai[11]认为由于r-FOV DWI降低了病灶和正常组织的平均体积，生成的ADC值更为准确。对于非活跃组和对照组的ADC测量值在r-FOV DWI上的评分较f-FOV DWI的ADC测量值接近的结果，主要是由于对照组的测量值比较高，推测可能与序列本身差异有关，也有可能是样本量较小导致的偏倚，还需要以后进一步探索。两种技术在病变组*vs.*对照组、活动组*vs.*非活动组诊断效能活动没有统计学差异，但非活动组*vs.*对照组AUC结果显示，全视野弥散加权成像优于小视野弥散加权成像（$P<0.05$）。活动组*vs.*对照组ROC比较没有结果，推测主要由于活动组测量的均为骨髓水肿处，ADC值与对照组骨髓ADC值差异较大，因此没有假阳性和假阴性病例。

本研究的局限性在于：各组样本量较小，以后将继续收集病例，扩大样本量；由于临床资料欠缺，未行两个序列ADC值与临床资料的相关性研究，待后续病例临床资料完善再进一步研究。

总之，小视野和全视野弥散加权成像ADC定量值在axSpA患者活动组、非活动组和对照组有统计学差异，诊断较能较好，f-FOV DWI序列在非活动组VS对照组中活动组诊断效能更优，而r-FOV DWI序列扫描时间更短，图像质量优于f-FOV DWI，两个序列均具有鉴别axSpA活动性的潜能，有望为临床axSpA诊断及分期提供精准定量信息。

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