Skeletal Radiol (2013) 42:209–217
DOI 10.1007/s00256-012-1372-y

SCIENTIFIC ARTICLE

MRI diagnosis of ACL bundle tears: value of oblique axial imaging

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Received: 31 December 2011 / Revised: 23 January 2012 / Accepted: 24 January 2012 / Published online: 21 February 2012

Abstract
Objective To investigate the diagnostic accuracy of oblique axial intermediate weighting MR imaging in detecting partial thickness anterior cruciate ligament (ACL) bundle tears.
Materials and methods The study protocol was approved by the institutional ethics committee. Sixty-one subjects (43 male, 18 female; mean age 27.4 years; range 9 to 57 years) with clinically suspected ACL tear or meniscal tear between September 2009 and January 2011 were studied with MRI and arthroscopy. Detection of partial tear for the ACL as a whole and for each ACL bundle by protocol A (standard orthogonal sequences) and protocol B (standard orthogonal sequences plus oblique axial intermediate weighted imaging) was compared in a blinded fashion. Performance characteristics for protocol A and protocol B were compared using sensitivity, specificity, accuracy and ROC curves. A two-tailed p value of <0.05 indicated statistical significance.
Results Fifteen (24.6%) normal, 15 (24.6%) partial and 31 complete tears were diagnosed by arthroscopy. Sensitivity, specificity and accuracy of protocol A for the diagnosis of partial tear of the ACL was 33%, 87% and 74%, while for protocol B the values were 87%, 87% and 87% respectively. The area under the curve (AUC) for the diagnosis of partial ACL tear and individual bundle tear was higher for protocol B, although this difference did not reach statistical significance (p>0.05).
Conclusion The addition of oblique axial imaging to standard MR imaging improves diagnostic accuracy for detecting partial tears of the ACL as well as individual bundle tears of the ACL.

Keywords Magnetic resonance imaging · Oblique axial · Knee · Anterior cruciate ligament · Tear

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Introduction

The anterior cruciate ligament is composed of the anteromedial and posterolateral bundles [1, 2]. Functionally, these two distinct bundles act in a complementary manner to limit excessive femorotibial movement at the end of flexion and extension [1–6]

Most anterior cruciate ligament (ACL) tears are complete, with the tear involving all of the anteromedial and posterolateral bundle fibres. Partial ACL tears occur less frequently and may involve both bundles to a variable degree or one bundle completely. In an arthroscopy study of 169 ACL tears, only 17 (10%) of tears were partial and these affected the anteromedial bundle more frequently than the posterolateral bundle [7]. That said, arthroscopic-based studies may reflect an underestimation of true prevalence as patients with complete rather than partial tears are more likely to undergo arthroscopy [7]. As well as accounting for patient symptoms, partial tear recognition is clinically relevant and important because:

1. Partial tears, unlike complete ACL tears, may have the capacity to heal with conservative treatment [8, 9]

2. One may be more inclined to opt for a trial of conservative treatment
3. If surgery is undertaken, partial ACL tears primarily limited to only a single bundle may be amenable to isolated single bundle graft augmentation rather than full ACL graft reconstruction [7, 10]

Clearly accurate early evaluation of partial ACL tears is relevant to improving the clinical and surgical management of ACL tears [8–11].

Usually, when partial ACL tears are diagnosed on MRI, it is frequently not possible to detect an isolated AM or PL bundle tear reliably using standard MR sequences and imaging planes [12]. Oblique sagittal and oblique coronal imaging has been used to delineate the ACL more clearly [13–17]. Recently, the value of oblique axial intermediate-weighted MR imaging in visualizing and discriminating the normal ACL bundles has been reported [13]. This prospective study was designed to determine the value of oblique axial imaging in evaluating individual ACL bundle tears. We hypothesized that the addition of oblique axial MR imaging to a standard knee MR protocol would improve delineation of individual ACL bundle tears.

Materials and methods

Subjects

The prospective study cohort was drawn from patients who underwent MRI knee examination followed by arthroscopy in our institution between September 2009 and January 2011. A total of 610 knee examinations with no history of knee surgery or arthroscopy were performed during the study period. Of these 610 knee examinations, 61 (10%) knees in 61 subjects (43 male, 18 female; mean age 27.4 years; range 9–57 years) underwent subsequent arthroscopy. As each patient had a single MRI examination followed by a single arthroscopy, 61 MRI examinations and 61 corresponding arthroscopy examinations were analysed. The time between MRI examination and arthroscopy was 1.1 month±1.8 month (1 day to 10 months).

MRI protocol

Magnetic resonance imaging examinations were performed on a 3-T imaging system (Philips X-series Best, Netherlands) using a phased array knee coil with eight elements. The knee was examined in a supine extended position. Standard MRI knee examination consisted of three sequences that comprised:

1. Turbo-spin-echo sagittal proton density-weighted imaging (TR 3,000 ms, TE 30 ms, bandwidth 291 Hz, TSE factor 10, 3-mm slice thickness, interslice gap 0.3 mm, voxel size 0.40 mm×0.54 mm, number of excitations 2, field of view 160 mm), planned in a plane parallel to the outer cortex of the lateral femoral condyle
2. Coronal T2-weighted fat suppression imaging (TR 2,800 ms, TE 60 ms, bandwidth 268 Hz, TSE factor 12, 3-mm slice thickness, interslice gap 0.3 mm, voxel size 0.50 mm×0.67 mm, number of excitations 2, field of view 160 mm)
3. Axial proton density weighted fat-suppression imaging (TR 3,000 ms, TE 30 ms, bandwidth 218 Hz, TSE factor 14, 3-mm slice thickness, interslice gap 0.3 mm, voxel size 0.45 mm×0.56 mm, number of excitations 2, field of view 150 mm)

This standard knee examination took about 15 min. Standard knee imaging was followed by oblique axial imaging of the ACL in which proton density-weighted (TR 3,000 ms, TE 30 ms, 3-mm slice thickness, interslice gap 0.3 mm, bandwidth 328 Hz, TSE factor 13, voxel size 0.25 mm×0.31 mm, number of excitations 2, field of view 120 mm) images were obtained in a plane aligned perpendicular to the course of the ACL using sagittal and coronal images for positioning and alignment (Fig. 1). This additional sequence took approximately 4 min to complete.

The standard knee protocol (proton density sagittal, T2-fat suppressed coronal, proton density fat-suppressed axial) was designated protocol A, while the standard knee protocol plus oblique axial imaging was designated protocol B.

MRI analysis

Two musculoskeletal radiologists (AWHN and EHHH; with 16 years and 10 years' experience of reporting musculoskeletal MRI respectively), who were unaware of the clinical or arthroscopic findings, reviewed all knee MR examinations and ACL status by consensus. Analysis was performed on a Digital Imaging and Communications in Medicine Viewer (OsiriX viewer). Firstly, the three standard imaging planes of the knee were evaluated (protocol A) with each ACL bundle being classified as intact, partially torn, or completely torn. Thereafter, these standard planes were evaluated together with oblique axial imaging of the ACL (protocol B) and each ACL bundle was again classified as intact, partially torn, or completely torn. Figure 2 showed normal appearance of anteromedial and posterolateral bundles on oblique axial images (Fig. 2).

An intact ACL or ACL bundle was one in which all the ACL fibres could be followed on contiguous sections as intact from the tibial to the femoral attachment. A partial ACL tear or ACL bundle tear was defined by high signal intensity within the ACL or individual bundle, focal swelling or thinning of the ACL or ACL bundle and/or a wavy

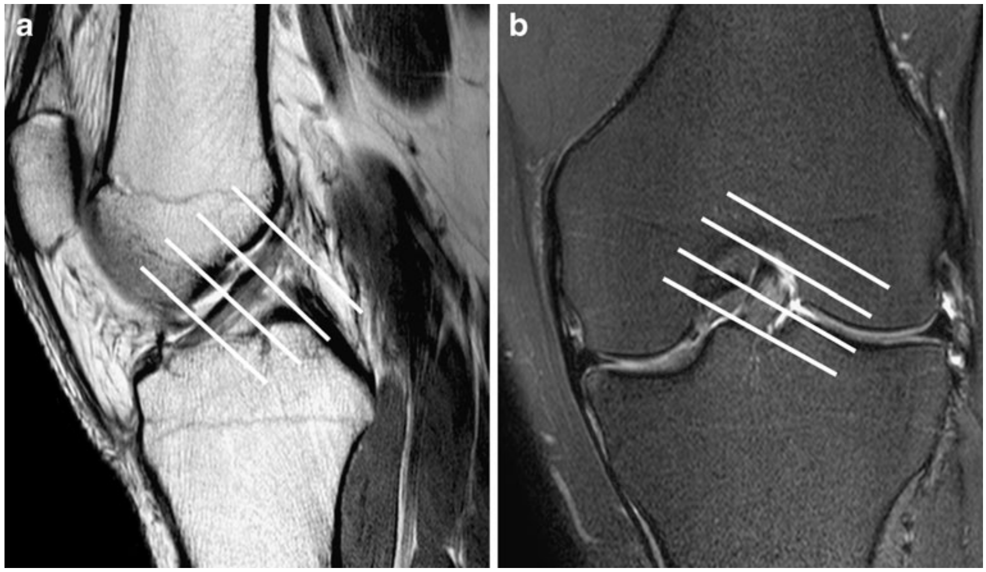

Fig. 1 Oblique axial intermediate-weighted imaging of the anterior cruciate ligament (ACL) was planned using **a** sagittal intermediate-weighted image (*white lines*) and **b** coronal T2-weighted fat-suppressed image (*white lines*). It could also be planned using analogous scout views

course of the ACL or ACL bundle with maintained continuity. A complete ACL tear or ACL bundle tear was defined as a complete lack of continuity of the ACL or ACL bundle tear [5, 14–20].

As well as assessing the individual bundles, the ACL as a whole unit was also classified on MRI as intact, partially torn, or completely torn. Intact ACL was defined by the normal appearance of both ACL bundles. Partial ACL tear was defined by either partial or complete tear in one or other bundle, but not a complete tear of both bundles. Complete ACL tear was defined by complete tear of both bundles. MRI results were compared with arthroscopic findings.

Arthroscopic analysis

All arthroscopies were performed by one of two orthopaedic surgeons, both with more than seven years' experience in knee surgery. They were aware of the MRI findings since these were necessary to determine the clinical need for arthroscopy. Standard anteromedial and anterolateral portals were used with blunt probing and distraction of the ACL to evaluate integrity and stability. At arthroscopy, each bundle was classified as normal, partially torn, or completely torn [8, 21, 22]. An intact ACL bundle was one in which the fibres were taut and visibly intact from the tibial to the femoral attachment. Partial ACL bundle tear was diagnosed when some, but not all bundle fibres were visibly torn on direct inspection and the remaining fibres exhibited expected resistance to deformation on physical probing. A complete bundle tear was diagnosed when there was no continuity of the ACL bundle and complete lack of tautness on direct probing. As well as individual bundle assessment, using the same diagnostic criteria, the whole ACL was also classified as normal, partially torn, or completely torn.

Statistical methods

Two analyses were performed with arthroscopic findings used as the reference standard. First, the sensitivity, specificity, and accuracy of protocol A compared with protocol B for detecting partial tears of the ACL as a whole and for individual bundle tears was calculated. Percentage values for sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV) and accuracy were rounded to the nearest whole number. Second, the receiver operating characteristic (ROC) curves representing overall performance were obtained. Differences between the two imaging protocols in terms of area under the ROC curve were analysed statistically using Wilcoxon signed-rank test. A two-tailed p value<0.05 indicated a statistically significant difference.

Results

At arthroscopy, 15 of the 61 knees examined (24.6%) had a normal ACL, 15 (24.6%) had a partial ACL tear and 31 (50.8%) had a complete ACL tear. For the AM bundle, 16 of the 61 knees examined (26%) were normal, 7 (12%) had a partial tear and 38 (62%) a complete tear. For the PL bundle, 15 of the 61 knees examined were normal (25%), 10 (16%) had a partial tear and 36 (59%) a complete tear.

Seven potential patterns of ACL partial tear are possible (Table 1). The most common pattern of partial tear at arthroscopy was a complete tear of the AM bundle together with a partial tear of the PL bundle. The next

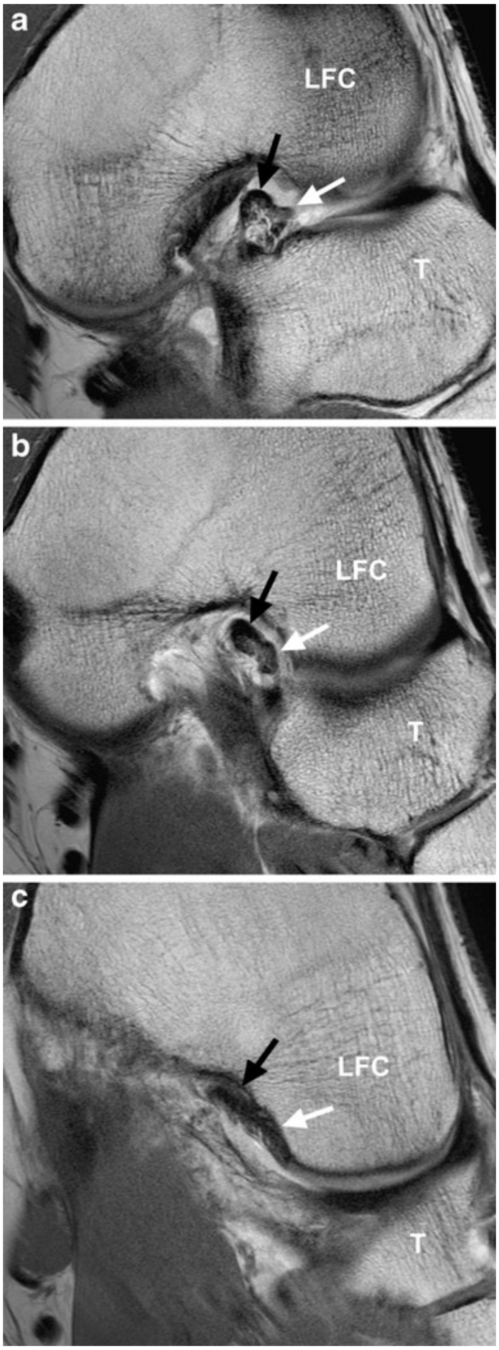

Fig. 2 Oblique axial intermediate-weighted oblique imaging in a 25-year-old man (same patient as in Fig. 1). Normal appearances of individual ACL bundles at **a** the tibial insertion, **b** the middle-third and **c** the femoral insertion. Both bundles are well separated. The anteromedial bundle (*black arrow*) is located in a more anterior and medial position, while the posterolateral (*white arrow*) bundle is located in a more posterior and lateral position. The bundles are considered intact as the fibres are taut, have continuity and normal signal intensity

most common type was a partial tear of the AM bundle together with a complete tear of the PL bundle (Table 1). Some examples of assessment of individual ACL bundle tear using oblique axial imaging (Fig. 3a–c).

Table 1 Pattern of tear present in 15 out of 61 knees with partial anterior cruciate ligament (ACL) tear (24.6%) out of potential combinations of partial ACL tear

Anteromedial bundle	Posterolateral bundle	Number (%) of cases
Normal	Partial tear	1 (7)
Normal	Complete tear	None
Partial tear	Normal	None
Partial tear	Partial tear	2 (13)
Partial tear	Complete tear	5 (33)
Complete tear	Normal	None
Complete tear	Partial tear	7 (47)

Accuracy for the diagnosis of complete or partial tears of the ACL (as a whole)

The sensitivity, specificity, PPV, NPV and accuracy of protocol A and protocol B for the diagnosis of partial tears of the ACL are shown in Table 2. In 6 out of 61 cases (10%), a complete ACL tear on protocol A was deemed a partial tear on protocol B, while in 2 out of 61 cases (3%), a normal bundle on protocol A was deemed a partial bundle tear on protocol B. All 8 discrepant cases between protocols A and B were found to be correctly diagnosed using protocol B, i.e. protocol B allowed accurate diagnosis in 8 more cases than protocol A, 6 of which were overestimated and 2 of which were underestimated using protocol A. The area under the curve (AUC) for diagnosis of ACL partial tear was higher for protocol B, although this difference did not reach statistical significance (p=0.42; Fig. 4a, Table 2).

Accuracy for the diagnosis of complete or partial tears of the anteromedial bundle

The sensitivity, specificity, PPV, NPV and accuracy of protocol A and protocol B for the diagnosis of complete or partial tear of the anteromedial bundle are shown in Table 2. In 3 out of 61 cases (5%), a complete anteromedial bundle tear on protocol A was deemed a partial anteromedial bundle tear on protocol B. All three cases were found to be overestimated on protocol A, i.e. protocol B provided an accurate diagnosis in three more cases than protocol A. The sensitivity, specificity and accuracy of MR imaging using protocol B for the diagnosis of anteromedial bundle partial tears was higher than for protocol A (Table 1). The area under the curve (AUC) for diagnosis of anteromedial bundle tears was higher for protocol B, although this difference did not reach statistical significance (p=0.65; Fig. 4b, Table 2).

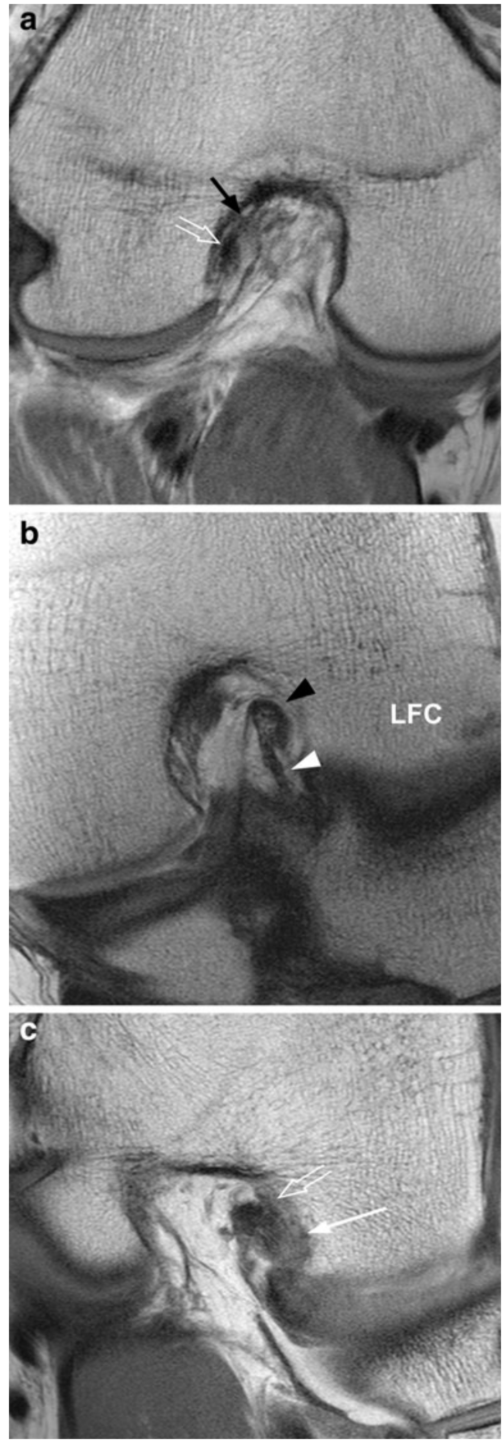

Fig. 3 Examples of assessment of individual ACL bundle tear using oblique axial imaging. The findings were all confirmed with arthroscopy. **a** MR imaging of the ACL in a 24-year-old man who suffered from injury of the knee. Oblique axial intermediate-weighted imaging of the ACL shows a complete tear of the anteromedial bundle (*black arrow*) and the mildly attenuated posterolateral bundle (*open arrow*), compatible with a partial tear of the posterolateral bundle. **b** MR imaging of the ACL in a 27-year-old woman with a twisting knee injury. Oblique axial intermediate-weighted imaging of the ACL shows a slightly swollen though otherwise intact anteromedial bundle (*black arrowhead*) and attenuated fibres of the posterolateral bundle (*white arrowhead*), compatible with a partial tear. **c** MR imaging of the ACL in a 22-year-old man with a twisting knee injury. Oblique axial intermediate-weighted imaging of the ACL shows a slightly swollen though otherwise normal anteromedial bundle (*open arrow*) and a high-signal posterolateral bundle (*long white arrow*), compatible with a partial tear of the posterolateral bundle. *LFC* lateral femoral condyle, *T* proximal lateral tibia

Accuracy for the diagnosis of complete or partial tears of the posterolateral bundle

The sensitivity, specificity, PPV, NPV and accuracy of protocol A and protocol B for the diagnosis of complete or partial tears of the posterolateral bundle are shown in Table 2. In 2 out of 61 cases (3%) a complete posterolateral bundle tear on protocol A was deemed a partial posterolateral bundle tear on protocol B, in 1 case a normal posterolateral bundle on protocol A was deemed a partial posterolateral tear on protocol B, while in 1 case a normal posterolateral bundle on protocol A was deemed a complete posterolateral bundle tear on protocol B. All 4 cases were confirmed to be correct using protocol B, i.e. 2 of these cases were underestimated using protocol A, while 2 were overestimated. The sensitivity, specificity and accuracy of MR imaging for protocol B in diagnosing PL bundle partial tear was higher than for protocol A (Table 2). The area under the curve (AUC) for diagnosis of posterolateral bundle tears was higher for protocol B, although this difference did not reach statistical significance (p=0.69; Fig. 4c, Table 2).

For either the anteromedial or the posterolateral bundle, none of the correct diagnoses was changed to an incorrect one with the addition of oblique axial imaging.

Discussion

Anterior cruciate ligament tears may vary from a small tear involving only part of a single bundle to a complete tear of both bundles. Although complete ACL tears do not have the capacity to heal, a limited blood supply to the ACL via the medial geniculate artery may allow healing of partial tears [8, 9]. Correct assessment regarding the presence, severity and location of partial tears is clinically relevant. Delayed recognition of a partial tear may result in progression to complete tear [8, 9, 22], while low-grade stable partial tears can be managed conservatively to good effect [8]. Assessment of individual bundle status is likely to be increasingly relevant to patient management with the introduction of new reconstructive techniques such as single bundle augmentation surgery, which has been advocated for patients who have a severe tear of only one rather than both bundles [7,

Table 2 Sensitivity, specificity, positive predictive value (*PPV*), negative predictive value (*NPV*) and accuracy of protocol A and protocol B for diagnosing partial tear of the ACL as a whole or tear of the individual anteromedial (AM) or posterolateral (PL) bundles. *AOC* area under curve

	Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)	Accuracy (%)	AOC	*P* (for AOC)
ACL as a whole							
Protocol A	33	87	45	89	74	0.507	0.42
Protocol B	87	87	68	95	87	0.613	
AM bundle tear							
Protocol A	29	86	20	90	79	0.536	0.65
Protocol B	71	82	33	96	80	0.611	
PL bundle tear							
Protocol A	30	94	50	87	84	0.505	0.69
Protocol B	60	94	67	92	89	0.564	

10, 23]. It stands to reason that each bundle should be individually evaluated on MRI as well as the ACL as a whole when an ACL tear is suspected.

Medium- to high-field strength MR imaging is known to have an accuracy of more than 95% for the diagnosis of an ACL tear, provided no distinction is made between a complete and a partial tear [24, 25]. The intermediate-weighted sequence is used to evaluate the ACL in this study owing to its favourable contrast and signal to noise ratio [26, 27]. Oblique coronal or oblique sagittal imaging of the ACL has been shown to improve the diagnosis of ACL tear, although no particular distinction between partial and complete tears was made in these studies [15–17, 28, 29]. In a study of 169 knees, 20 of whom had a partial ACL tear, oblique coronal imaging aligned parallel to the ACL improved the diagnostic accuracy of ACL tear [14], although again, no distinction between partial and complete ACL tear was made.

The accuracy of MRI in diagnosing partial tear of the ACL is much lower than for complete ACL tear with published data indicating a sensitivity of 40–77% and a specificity of 62–89% [5, 19, 30–34]. In the current study, the sensitivity and specificity of MRI in diagnosing partial ACL tear using standard views were 33% and 87% respectively, which is in line with published data. The reduced accuracy of standard MR imaging in diagnosing partial ACL tear is related to the oblique orientation of the ACL, its relatively fine fibrillar structure, as well as oedema, swelling and haemorrhage impeding accurate delineation of a partial tear.

Oblique axial imaging improves visualisation of normal ACL bundles over standard MR imaging [13]. Oblique axial imaging allows the ACL to be assessed on 6–8 consecutive images rather than 2–3 images as in sagittal or coronal imaging, and also provides a true axial view of the ACL, minimising the magic angle effect and partial volume artefact [13]. This study shows that oblique axial imaging improves diagnostic accuracy for partial ACL tears. The addition of an oblique axial view to standard MR imaging of the knee increased the sensitivity for the diagnosis of partial tears from 33 to 87% and accuracy from 74 to 87%, while the specificity remained unaltered at 87%. Whilst it was not possible to correctly distinguish partial and complete ACL tears using standard views in 11 of the 46 ACL tears encountered in this study, additional oblique axial imaging of the ACL allowed 6 of these 11 cases to be correctly distinguished.

Almost all previous MR-based studies addressing partial tears of the ACL [5, 19, 30–34] have considered the ACL as a whole unit and have not investigated the accuracy of MRI in diagnosing individual ACL bundle tear. A bundle-specific approach would seem to be of greater clinical relevance given that “partial tear of the ACL” may conceivably comprise a partial tear of both bundles, a partial tear of a single bundle and/or a complete tear of one bundle. In a recent study by Van Dyck et al., standard plane imaging (coronal, sagittal and axial) was used to classify ACL tear into isolated AM and PL bundle tear [12]. Only 3 isolated bundle tears were identified out of 51 patients with ACL partial tear. It was concluded that it was not possible to localize a partial tear to the AM or PL bundle using standard MR sequences and imaging planes. The current study evaluated, to our knowledge for the first time, the accuracy of MR imaging in detecting tears of individual AM and PL bundles using oblique imaging. The sensitivity, specificity and accuracy of standard MR imaging for the detection of anteromedial bundle partial tears was shown to be 29%, 86% and 79%, while that for posterolateral bundle tears was 30%, 94% and 84% respectively. However, the addition of oblique axial imaging to standard views improved accuracy in diagnosing individual ACL bundle tears. The addition of oblique axial imaging, increased sensitivity for anteromedial bundle partial tear to 71% while specificity (82%) and accuracy (80%) remained similar. For posterolateral bundle partial tear, the sensitivity increased to 60%, while specificity and accuracy remained similar.

Volumetric imaging offers an opportunity to reconstruct different planes in the evaluation of the ACL [35–37]. The reconstructed oblique axial plane of the ACL may help to evaluate the status of anterior cruciate ligament and shorten the imaging time. Further studies are required to investigate

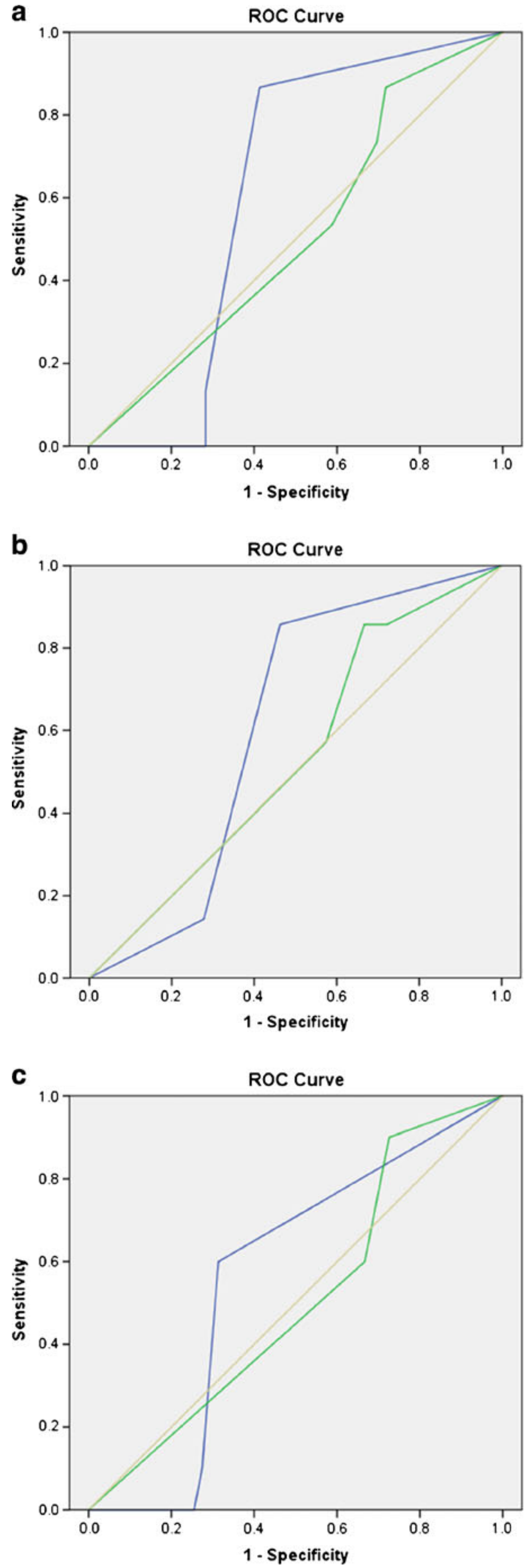

Fig. 4 Receiver operating characteristic curves for identification of a partial tear of **a** overall ACL, **b** anteromedial bundle and **c** posterolateral bundle. Each *diagonal yellow line* represents performance equal to chance and has an area under the curve of 0.5. Perfect performance would have an area of 1.0. Each *green line* represents performance with a standard protocol alone; the *blue line* represents performance with the addition of an oblique axial sequence

the diagnostic value of the reconstructed oblique axial images.

There are some limitations to this study. First, there is a selection bias because we included only those patients who later underwent surgery. Second, the consensus evaluation by two radiologists undertaken in this study may not reflect true clinical practice and independent validation would be helpful. Also, it is not possible to blind the observers to the two different techniques. Third, as oblique axial imaging of the ACL was compared with standard MR knee imaging, further studies comparing this plane with oblique coronal or oblique sagittal MR imaging of the ACL or analogous reconstructions using 3D isotropic datasets would be helpful. Fourth, arthroscopy was used as a reference standard for individual bundle tears, despite arthroscopy relying on a combination of direct and indirect signs to diagnose individual bundle tears, since it is not always possible to directly visualise all parts of both bundles on arthroscopy [23, 30, 32]. Finally, arthroscopic findings could have been biased by the availability of the MRI reports at the time of arthroscopy.

As we have incorporated oblique axial imaging of the ACL into our routine clinical practice, we will be able to address some of the limitations outlined in later studies. Although oblique axial imaging may lead to some ACL tears that are considered to be complete tears on standard imaging being re-graded as partial tears, in clinical practice, making a distinction between a complete tear and a high-grade partial tear may not be that relevant as both tears are treated in a similar manner. Although difficult to demonstrate in a relatively small study as that presented, at this juncture we believe that oblique axial imaging of the ACL will prove to be of most practical clinical benefit in:

1. Affirming normality or abnormality of the ACL if relatively minor ACL injury is suspected on standard orthogonal views
2. Demonstrating small partial ACL tears when the ACL is considered normal on standard views
3. Determining the site and extent of an individual bundle injury, when a partial tear of the ACL is shown on standard views

In conclusion, compared with standard MR imaging, the addition of oblique axial imaging improves diagnostic accuracy for detecting partial tears of the ACL as well as assessment of individual bundle tears. This imaging plane seems to provide a useful adjunct to standard MR imaging when ACL tear is suspected.

Acknowledgements The work described in this paper was partially supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No.SEG_CUHK02).

Special thanks to Jason Leung for his great help in calculating and interpreting the statistics part of this manuscript.

References

1. Amis AA, Dawkins GP. Functional anatomy of the anterior cruciate ligament. Fibre bundle actions related to ligament replacements and injuries. J Bone Joint Surg Br. 1991;73:260–7.
2. Girgis FG, Marshall JL, Monajem A. The cruciate ligaments of the knee joint. Anatomical, functional, and experimental analysis. Clin Orthop Relat Res. 1975;106:216–31.
3. Fuss FK. Anatomy of the cruciate ligaments and their function in extension and flexion of the human knee joint. Am J Anat. 1989;184:165–76.
4. Norwood LA, Cross MJ. Anterior cruciate ligament: functional anatomy of its bundles in rotatory instabilities. Am J Sports Med. 1979;7:23–6.
5. Umans H, Wimpfheimer O, Haramati N, et al. Diagnosis of partial tear of the anterior cruciate ligament of the knee: value of MR imaging. AJR Am J Roentgenol. 1995;165:893–7.
6. Wu JL, Hosseini A, Kozanek M, Gadikota HR, Gill TJ IV, Li G. Kinematics of the anterior cruciate ligament during gait. Am J Sports Med. 2010;38:1475–82.
7. Ochi M, Adachi N, Deie M, Kanaya A. Anterior cruciate ligament augmentation procedure with a 1-incision technique: anteromedial bundle or posterolateral bundle reconstruction. Arthroscopy. 2006;22:463.e1–5.
8. Noyes FR, Mooar LA, Moorman CT III, McGinniss GH. Partial tears of the anterior cruciate ligament. Progression to complete ligament deficiency. J Bone Joint Surg Br. 1989;71:825–33.
9. Sommerlath K, Odensten M, Lysholm J. The late course of acute partial anterior cruciate ligament tears. A nine to 15-year follow-up evaluation. Clin Orthop Relat Res. 1992;281:152–8.
10. Siebold R, Fu FH. Assessment and augmentation of symptomatic anteromedial or posterolateral bundle tears of the anterior cruciate ligament. Arthroscopy. 2008;24:1289–98.
11. Cohen SB, VanBeek C, Starman JS, Armfield D, Irrgang JJ, Fu FH. MRI measurement of the 2 bundles of the normal anterior cruciate ligament. Orthopedics. 2009;32:(9).
12. Van Dyck P, De Smet E, Veryser J, Lambrecht V, Gielen JL, Vanhoenacker FM, et al. Partial tear of the anterior cruciate ligament of the knee: injury patterns on MR imaging. Knee Surg Sports Traumatol Arthrosc. 2012;20:256–61.
13. Ng WHA, Griffith JF, Law KY, Ting JW, Tipoe GL, Ahuja AT, et al. Oblique axial MR imaging of the normal anterior cruciate ligament bundles. Skeletal Radiol. 2012;40:1587–94.
14. Hong SH, Choi JY, Lee GK, Choi JA, Chung HW, Kang HS. Grading of anterior cruciate ligament injury. Diagnostic efficacy of oblique coronal magnetic resonance imaging of the knee. J Comput Assist Tomogr. 2003;27:814–9.
15. Smith DK, May DA, Phillips P. MR imaging of the anterior cruciate ligament: frequency of discordant findings on sagittal-oblique images and correlation with arthroscopic findings. AJR. 1996;166:411–3.
16. Katahira K, Yamashita Y, Takahashi M, et al. MR imaging of the anterior cruciate ligament: value of thin slice direct oblique coronal technique. Radiat Med. 2001;19:1–7.
17. Duc SR, Zanetti M, Kramer J, Käch KP, Zollikofer CL, Wentz KU. Magnetic resonance imaging of anterior cruciate ligament tears: evaluation of standard orthogonal and tailored paracoronal images. Acta Radiol. 2005;46:729–33.
18. Chen WT, Shih TT, Tu HY, Chen RC, Shau WY. Partial and complete tear of the anterior cruciate ligament. Acta Radiol. 2002;43:511–6.
19. Van Dyck P, Vanhoenacker FM, Gielen JL, Dossche L, Van Gestel J, Wouters K, et al. Three tesla magnetic resonance imaging of the anterior cruciate ligament of the knee: can we differentiate complete from partial tears? Skeletal Radiol. 2011;40:701–7.
20. Tung GA, Davis LM, Wiggins ME, Fadale PD. Tears of the anterior cruciate ligament: primary and secondary signs at MR imaging. Radiology. 1993;188:661–7.
21. Farquharson-Roberts MA, Osborne AH. Partial rupture of the anterior cruciate ligament of the knee. J Bone Joint Surg Br. 1983;65:32–4.
22. Bak K, Scavenius M, Hansen S, Nørring K, Jensen KH, Jørgensen U. Isolated partial rupture of the anterior cruciate ligament. Long-term follow-up of 56 cases. Knee Surg Sports Traumatol Arthrosc. 1997;5:66–71.
23. Petersen W, Zantop T. Partial rupture of the anterior cruciate ligament. Arthroscopy. 2006;22:1143–5.
24. Lee JK, Yao L, Phelps CT, Wirth CR, Czajka J, Lozman J. Anterior cruciate ligament tears: MR imaging compared with arthroscopy and clinical tests. Radiology. 1988;166:861–4.
25. Mink JH, Levy T, Crues JV III. Tears of the anterior cruciate ligament and menisci of the knee: MR imaging evaluation. Radiology. 1988;167:769–74.
26. Kowalchuk RM, Kneeland JB, Dalinka MK, Siegelman ES, Dockery WD. MRI of the knee: value of short echo time fast spin-echo using high performance gradients versus conventional spin-echo imaging for the detection of meniscal tears. Skeletal Radiol. 2000;29:520–4.
27. Yao L, Pitts JT, Thomasson D. Isotropic 3D fast spin-echo with proton-density-like contrast: a comprehensive approach to musculoskeletal MRI. AJR Am J Roentgenol. 2007;188:W199–201.
28. Kwon JW, Yoon YC, Kim YN, et al. Which oblique plane is more helpful in diagnosing an anterior cruciate ligament tear? Clin Radiol. 2009;64:291–7.
29. Do-Dai DD, Stracener JC, Youngberg RA. Oblique sagittal MRI of anterior cruciate ligament. J Comput Assist Tomogr. 1994;18:160–2.
30. DeFranco MJ, Bach Jr BR. A comprehensive review of partial anterior cruciate ligament tears. J Bone Joint Surg Am. 2009;91:198–208.
31. Yao L, Gentili A, Petrus L, Lee LK. Partial ACL rupture: an MR diagnosis? Skeletal Radiol. 1995;24:247–51.
32. Brandser EA, Riley MA, Berbaum KS, el-Khoury GY, Bennett DL. MR imaging of anterior cruciate ligament injury: independent value of primary and secondary signs. Am J Roentgenol. 1996;167:121–6.
33. Roychowdhury S, Fitzgerald SW, Sonin AH, Peduto AJ, Miller FH, Hoff FL. Using MR imaging to diagnose partial tears of the anterior cruciate ligament: value of axial images. AJR Am J Roentgenol. 1997;168:1487–91.
34. Van Dyck P, Gielen JL, Vanhoenacker FM, Wouters K, Dossche L, Parizel PM. Stable or unstable tear of the anterior cruciate ligament of the knee: an MR diagnosis? Skeletal Radiol. 2012;41:273–80.

35. Subhas N, Kao A, Freire M, Polster JM, Obuchowski NA, Winalski CS. MRI of the knee ligaments and menisci: comparison of isotropic-resolution 3D and conventional 2D fast spin-echo sequences at 3T. AJR Am J Roentgenol. 2011;197(2):442–50.
36. Jung JY, Yoon YC, Kwon JW, Ahn JH, Choe BK. Diagnosis of internal derangement of the knee at 3.0-T MR imaging: 3D isotropic intermediate-weighted versus 2D sequences. Radiology. 2009;253(3):780–7.
37. Kijowski R, Davis KW, Woods MA, Lindstrom MJ, De Smet AA, Gold GE, et al. Knee joint: comprehensive assessment with 3D isotropic resolution fast spin-echo MR imaging—diagnostic performance compared with that of conventional MR imaging at 3.0T. Radiology. 2009;252(2):486–95.