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Viewpoint

A new way of grading severity of ACL rupture on acute MRI to consider potential for non-surgical healing with the Cross Bracing Protocol: ACL Acute Rupture Characteristics for Healing (ACL-ARCH) MRI criteria

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1. Summary

In this paper, we introduce a new way of grading acute ACL rupture on MRI to assess features that are relevant to ACL healing potential, based on experience managing 1080 active individuals and athletes with the Cross Bracing Protocol. We describe the following features of acute ACL injury visible on MRI: i) tibial/femoral attachment integrity; ii) ACL tissue displacement outside the intercondylar notch; iii) the distance between the ends of the ruptured ACL ('gap distance'); and iv) retraction of ACL ends into rounded stumps ('involution'). We hope these observations inspire further research to assess the potential for these variables to predict an optimal healing outcome and inform treatment decisions.

2. The importance of ACL rupture severity

In the early 1900's, most ACL ruptures went undiagnosed and untreated, and surgery was reserved to treat "severe disability in which surgical repair was the only hope of normal function".[1] Typically, an ACL injury would only be diagnosed in cases of persistent instability, and surgery would only be utilised after trying a period of conservative management first.[2] With the emergence of early diagnostic techniques and less invasive surgeries, there was a shift towards treating most ACL ruptures with early surgery. We now know not everyone requires an ACL reconstruction (ACLR) to achieve knee stability after ACL rupture,[3] and people who experience chronic knee instability benefit most from ACLR.[4] However, we lack criteria to predict ACL treatment outcomes and inform early treatment decisions for people who suffer an ACL rupture.

3. A paradigm shift in ACL rupture classification

We propose that there is a spectrum of ACL rupture severity, and that greater ACL rupture severity corresponds with more force on the knee at the time of injury. We hypothesise that the least severe ACL ruptures may be the most likely to have successful outcomes and heal when managed with rehabilitation alone. As the severity of ACL rupture increases, the Cross Bracing Protocol (CBP)[5] may be a useful adjunct to assist with ACL healing by using the principles of reduction (i.e. 90° of knee flexion reduces the gap distance between the ruptured ACL remnants) and immobilisation (i.e. immobilising the knee in a brace). Furthermore, in our experience the most severe ACL ruptures are the least likely to achieve an optimal heal and may benefit from early ACLR. Analogous to the role of imaging in the triage of bony fractures, we propose new MRI criteria that reflect ACL rupture severity with potential to inform treatment decisions.

4. We now know ACLs can heal, but not all healing is equivalent

Recent evidence suggests that approximately 1-in-3 active adults who rupture their ACL will regain continuity of fibres if managed with rehabilitation alone.[6] Further, immobilising the knee with the ruptured ACL in a shortened position using a knee brace could assist in facilitating healing with 90 % of people regaining continuity of fibres after 3 months of treatment with the CBP.[5] However, not all ACLs that regained continuity of fibres in these studies had a normal ACL appearance on MRI.[5,6] In the KANON trial, 50 % of people with a continuous ACL on 2-year MRI had a normal appearance ACL, whilst 50 % had a thinned/elongated continuous ligament.[6] In people with a continuous ligament 3-months after treatment with the CBP, 56 % had a thick ligament with normal course, whilst 44 % had a thinned/elongated continuous ligament.[5] Our recent CBP study found that people with a thick ACL with normal course at 3 months had better 12 month outcomes than

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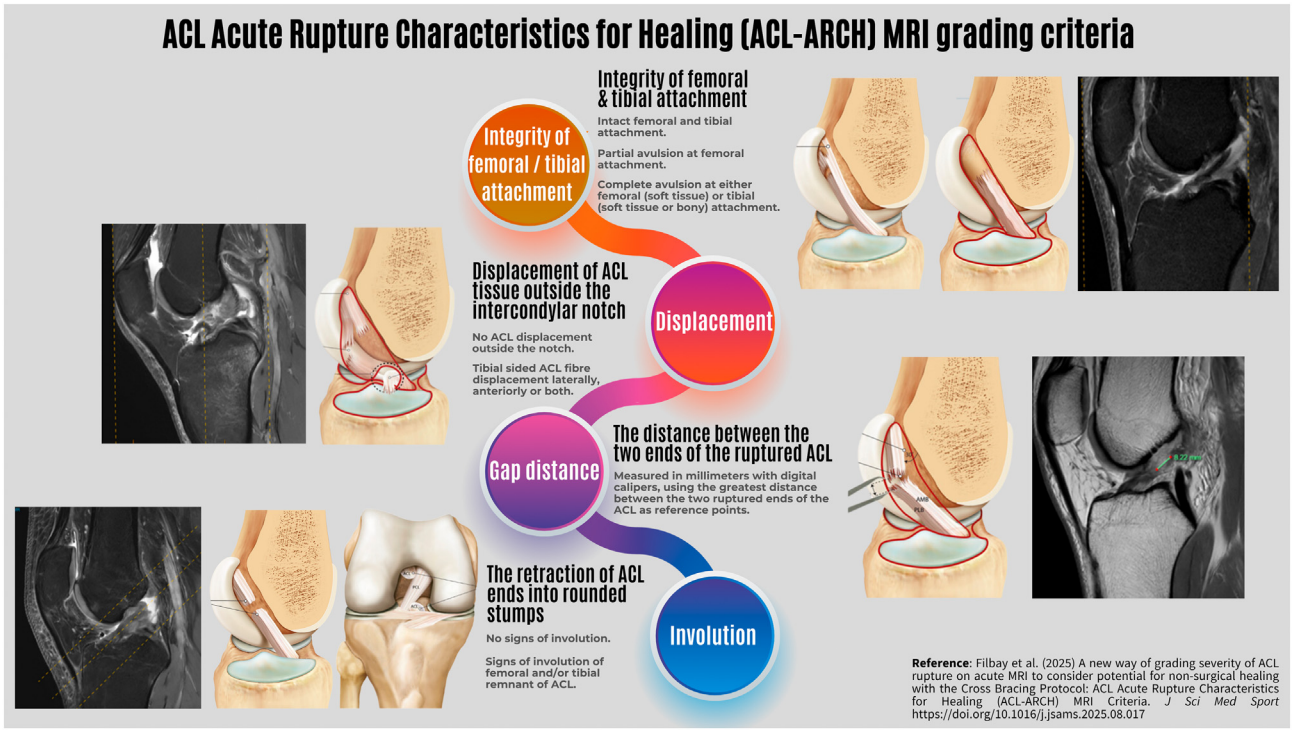

Fig. 1. An overview of the ACL Acute Rupture Characteristics for Healing (ACL-ARCH) MRI criteria.

others, including self-reported knee function, quality of life, passive knee laxity and return to sport.[5]

5. Introducing the ACL Acute Rupture Characteristics for Healing (ACL-ARCH) MRI criteria

After managing over 1080 people with the CBP, we believe the following characteristics (Fig. 1) may affect the likelihood of achieving an optimal healing outcome (i.e., thick/taut/normal appearance) with non-surgical management. In addition to grading the standard features of ACL injury on MRI, including any concomitant injuries (e.g. meniscal injury, concomitant ligament injury, cartilage damage, osteoarthritis features, bone bruising, joint effusion), we recommend assessment of four additional ACL rupture characteristics, outlined in Fig. 1.

5.1. Integrity of ACL femoral/tibial attachment

MRI findings from the first 80 people who were managed with the CBP (including recreational, competitive and professional athletes; 39 % were female) suggest that people with partial avulsion of ACL tissue from the femoral attachment (Fig. 1) may be more likely to achieve a suboptimal heal (thinned/elongated) or no healing, compared to people with their femoral origin intact (Table 1).[5] We hypothesise that the ACL tissue that is avulsed from the femoral attachment is unlikely to re-attach to the femoral footprint, corresponding to a suboptimal (thinned/elongated) heal in most cases. Very few individuals with all ACL tissue detached from the femoral or tibial attachment have been managed with the CBP. Although it is presumed that such individuals have a low potential for healing, further research is needed.

5.2. Displacement of ACL tissue outside the intercondylar notch

We believe that displacement of ACL tissue outside the intercondylar notch is associated with the likelihood of a suboptimal healing outcome when managed with the CBP. This includes instances where all or some of the distal remnant of the ACL has flipped anteriorly and/or laterally under the lateral femoral condyle (Fig. 1). Within the first 80 people managed with the CBP, displacement was most common amongst people who achieved a thinned/elongated heal (78 %) or no healing (88 %) (Table 1).[5] In comparison, 45 % of people with a thick/taut heal had displacement of ACL fibres on acute MRI (Table 1).[5] We hypothesise that displacement of ACL tissue outside the intercondylar notch indicates a significant disruption to the synovial sheath that encapsulates the ACL. Disruption of the synovial sheath has previously been theorised to negatively impact healing potential.[7] The most common outcome for people with displacement of ACL tissue outside the intercondylar notch

Table 1
Baseline MRI findings in the first 80 people treated with the CBP, based on ACL healing status on 3 month MRI.

	Continuous, thick and taut ACL with normal alignment (ACLOAS 1) n = 40	Continuous, thinned and/or elongated ACL (ACLOAS 2) n = 32	Discontinuous ACL or attached to PCL (ACLOAS 3) n = 8
Integrity of ACL femoral attachment: partial avulsion	7 (18 %)	29 (91 %)	8 (100 %)
Displacement of ACL tissue outside the intercondylar notch	18 (45 %)	25 (78 %)	7 (88 %)
Gap distance between the two ends of the ruptured ACL			
1–3 mm	9 (23 %)	3 (9 %)	0 (0 %)
4–6 mm	24 (60 %)	10 (31 %)	1 (12.5 %)
≥7 mm	7 (18 %)	19 (59 %)	7 (87.5 %)

was a suboptimal (thinned/elongated) heal or non-heal on 3-month MRI (Table 1), which might be explained by a failure of these disrupted tissues to reattach to the proximal remnant of the ACL.

5.3. Gap distance between the two ends of the ruptured ACL

We believe there is an association between the distance between the two ends of the ruptured ACL, and the potential for an optimal healing outcome when managed with the CBP. Specifically, people with a large gap distance between the ruptured ACL remnants (assessed by measuring the largest distance between the torn ends of the ACL) may be less likely to achieve an optimal healing outcome compared to people with a smaller gap distance. Within the first 80 people managed with the CBP, 7 out of 40 (18 %) who achieved a thick/taut heal had a gap distance of ≥ 7 mm on acute MRI, compared to 19 out of 32 (59 %) who achieved a thinned/elongated heal, and 7 out of 8 (88 %) people who had no ACL healing at 3 months (Table 1). The rationale for immobilising the knee in 90 degree flexion is to reduce the gap between the torn ACL ends, and therefore assist with facilitating healing between the torn remnants.[5] When a large gap distance between the torn ends of the ACL is present, the CBP may be ineffective in achieving an adequate reduction of the injured ACL tissues.

5.4. The retraction of ACL ends into rounded stumps — 'involution'

We have observed the phenomenon of ACL involution on MRI, where one or both ends of the ruptured ACL appear rounded and retracted. We have observed this most commonly in people who present for MRI more than 3 weeks after acute ACL rupture. This could reflect the early stages of a 'non-heal' (analogous to a 'non-union' of a fractured bone) and may correspond to epiligament regeneration around the ruptured ACL ends[8] forming a histological barrier to healing, although this hypothesis requires further research.

6. How to assess the ACL-ARCH on MRI

We recommend a minimum 1.5 T MRI, with 3 T MRI being preferrable for superior image quality and spatial resolution, enabling greater visualisation of the ACL injury. We also recommend additional 'double oblique' sequences to enable greater visualisation of the ACL fibres. Appendix 1 outlines the recommended MRI acquisition and sequences to optimise ACL visualisation. In Fig. 1, we summarise how to categorise these variables on MRI and provide example illustrations and MRIs for each feature. In Appendix 2, we provide further guidance for assessment on MRI and reporting of findings.

7. Key considerations and knowledge gaps

With further research, we believe that acute MRI features will assist with estimating the likelihood of individuals achieving an optimal heal with nonsurgical management. This could assist people with ACL rupture in making an informed treatment decision, acknowledging that individuals have different treatment preferences and goals and are willing to accept different levels of risk when it comes to the likelihood of achieving a successful outcome with non-surgical vs. surgical treatment.

Further research is needed to compare the function, physiology and histology between a thick/taut heal and a thinned/elongated heal, and to compare the MRI appearance of the ACL with the uninjured contralateral side. People with a thick/taut heal on 3-month MRI reported better outcomes than those with a thinned/elongated heal or no ACL healing, at 12 months.[5] However, average outcomes in people with a thinned/elongated heal (e.g., Lysholm Scale score 91 out of 100 at 12 months, ACLQOL score of 70 out of 100 at 12 months, 71 % returned to pre-injury sport) were not dissimilar to those observed post ACL-reconstruction.[9,10] Longer-term studies are needed to understand the relationship between the quality of ACL healing, and the rate of ACL re-rupture. We hypothesise that thinned/elongated heals may re-rupture at a higher rate than thick/taut heals in people who return to cutting and pivoting sport, although further research is needed to confirm this hypothesis, and to compare this with the rate of graft rupture after ACLR.

We are conducting a number of studies to address key knowledge gaps. This includes developing and testing a predictive model for optimal ACL healing following management with the CBP, and performing a randomised controlled trial to compare the clinical effectiveness of the CBP compared to early ACLR for the management of acute ACL rupture. In the meantime, we share here our clinical observations and hypotheses related to the severity of ACL rupture and subsequent healing potential, to assist with advancing research in this area. The suitability of assessing these features on MRI in clinical practice needs to be assessed, including assessment of intra- and inter-rater reliability.

Confirmation of ethical compliance

The data reported in the article is from a research project that has been approved by Human Research Ethics Committee of The University of Melbourne (#22080). Participants gave informed consent to participate in the study before taking part.

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CRediT authorship contribution statement

S.R. Filbay: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization. **M. Dowsett:** Conceptualization, Investigation, Data curation, Writing – review & editing. **M. van Haeringen:** Investigation, Data curation, Writing – review & editing. **E. Palmer:** Writing – review & editing. **G. Roger:** Conceptualization, Writing – review & editing. **P. Lucas:** Conceptualization, Writing – review & editing. **A. van Den Heever:** Conceptualization, Writing – review & editing. **R. Sabharwal:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – review & editing. **T. Cross:** Conceptualization, Methodology, Investigation, Resources, Writing – review & editing.

Declaration of interest statement

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: SF is an Associate Editor of JSAMS and has received travel reimbursement to present at international conferences on the topic of ACL injury and has received reimbursement for presenting to clinicians on the topic of ACL injury, for various organisations. TC has received travel reimbursement to present at conferences, including a conference organised by Medi. Bauerfeind Germany donated 100 braces to TC for use in clinical practice. TC has run paid courses for health professionals on the Cross Bracing Protocol. All other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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The original idea in 2014 to test the hypothesis that adopting what was to become named the "Cross Bracing Protocol" would achieve a "closed reduction and immobilisation" of the acutely ruptured ACL tissues and potentially facilitate the natural healing of the injured ACL is attributed to Dr Mervyn Cross. Despite being a retired Orthopaedic knee surgeon, Dr Mervyn Cross contributed most significantly to the CBP research right up to his passing in August 2023.

Appendix 1. Recommended MRI protocol to assess ACL Acute Rupture Characteristics for Healing (ACL-ARCH) MRI criteria

Routine knee MRI with additional double oblique sequences

MRI acquisition

We recommend a 3 T MRI scanner (preferrable) or a 1.5 T MRI scanner (preferably with AIR recon DL/Deep Resolve installed) using a phased array body coil. 1.5 T scanners should only be used if they have AIR recon DL/Deep Resolve installed to maximise resolution and optimise visualisation of the ACL.

1. Acquire routine knee series as per usual practice for evaluation of suspected ACL and/or meniscus injury:
   - Sagittal proton density-weighted non-fat-suppressed sequence (Sag PD)
   - Coronal proton density-weighted non-fat-suppressed sequence (Cor PD)
   - Coronal proton density-weighted fat-suppressed sequence (Cor PD FS)
   - Sagittal proton density-weighted fat-suppressed sequence (Sag PD FS)
   - Axial proton density-weighted fat-suppressed sequence (Ax PD FS)
2. Acquire the following "double oblique" sequences to complement routine knee series and improve visualisation of the injured ACL:
   - 1.5 mm slice thickness, 0.3 mm spacing, 14 FOV, approximately 18 slices.
   - Acquisition time under 4 min to limit motion artefact.
   - *Within 6 weeks of acute knee injury and/or where heavy oedema is present*: Coronal oblique proton density-weighted fat-suppressed sequence (Cor Obl PD FS)
   - Suggested parameters: 35 ms, TR: 4000 ms, frequency encoding: 400, phase encoding: 360, bandwidth: 62.5, ETL: 11, right to left phase direction, with 'Air Recon DL' for GE.

Appendix 2. ACL Acute Rupture Characteristics for Healing (ACL-ARCH) MRI criteria: guidance for assessment on MRI and reporting of findings

	How to assess on MRI	How to report findings
Integrity of ACL femoral and tibial attachments	Sagittal sequences initially used to assess if femoral or tibial ACL attachments are completely avulsed. If not completely avulsed, use axial, coronal and double-oblique sequences to assess for partial femoral avulsion or intrasubstance delamination which appear as a fluid signal intensity tear/cleft at the femoral footprint.	i) Intact femoral and tibial ACL attachments, ii) Partial avulsion at the femoral origin/tibial insertion or iii) Complete avulsion at either the femoral origin (soft tissue) or tibial insertion (soft tissue or bony).
Displacement of ACL tissue outside the intercondylar notch	On coronal, sagittal and double-oblique sequences, look for tibial end fibres of ACLi) which appear as similar signal intensity to remainder of the ACL that are displaced laterally beneath the lateral femoral condyle and/or anteriorly to lie superior to the tibial attachment of the ACL.	No ACL displacement outside the notch, ii) Tibial sided ACL fibre displacement laterally, anteriorly or both. Quantify if this represents less than or more than 20 % of the volume of the ACL (i.e. 80 % or more of the ACL fibres are within the notch).
Gap distance between the two ends of the ruptured ACL	The gap distance is the maximum distance between the tibial and femoral ends of the ACL at the rupture zone. This is best assessed on the sagittal PD sequence.	The gap distance is measured (using a digital calliper) and reported in millimetres.
The retraction of ACL ends into rounded stumps (involution)	Look for round, capped-over, smooth and well demarcated ends of the ruptured ACL, at the proximal (femoral) and/or tibial (distal) ACL remnant. All MRI sequences are helpful to assess involution.	i) No signs of involution, ii) Signs of involution of femoral and/or tibial remnant of the ACL

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