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# Magnetic resonance imaging as a tool for evaluation of traumatic knee injuries

## Anatomical and pathoanatomical correlations*

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### ABSTRACT

Traumatic injury to the knee remains a diagnostic and therapeutic challenge. Magnetic resonance imaging (MRI) has been applied to musculoskeletal pathoanatomy and has been shown to be an effective tool for definition and characterization of knee pathology. A systematic approach is taken to establish anatomical and pathoanatomical correlations, as well as the role of MRI in the management of knee injuries.

Imaging was performed at the UCLA Medical Center using a permanent magnet system and a combination of solenoidal surface coils and thin-section, high-resolution scanning techniques. Images depict structural anatomical and spatial details of the knee that correlate well with corresponding cadaveric cryosections. To determine pathoanatomical correlations and the efficacy of MRI, 105 patients with preoperative diagnoses of meniscal tears, anterior and posterior cruciate ligament tears, tibial plateau fracture, and patella and quadriceps injuries were imaged.

Results indicated that for the medial meniscus MRI demonstrated a 95.7% sensitivity, 81.8% specificity, 90% accuracy, 88.2% positive predictive value (PPV), and 93.1% negative predictive value (NPV). Imaging of the lateral meniscus demonstrated a 75% sensitivity, 95% specificity, 91% accuracy, 80% PPV, and 94% NPV. MRI of the ACL revealed 100% sensitivity, specificity, accuracy, positive and negative predictive values.

MRI is a noninvasive tool which uses no ionizing radiation and can accurately define and characterize anatomy and pathoanatomy. This study indicates that MRI in conjunction with clinical evaluation can contribute to treatment decision-making processes and assist in preoperative planning. An algorithm demonstrating the potential clinical use of MRI is presented.

Traumatic injury to the knee has always been a diagnostic and therapeutic challenge to minimize morbidity and maximize potential performance. Orthopaedic surgeons have made great strides to maximize clinical results through developments in innovative diagnostic techniques, arthroscopic surgery, and creative protocols in rehabilitation. MRI is a technique that noninvasively maps the magnetic behavior of body tissues in a multiplanar reconstructive manner.[16] Historically, Block and Purcell discovered the nuclear magnetic resonance (NMR) phenomenon that eventually won them the Nobel prize in physics in 1952. However, it was not until the early 1970s that Damadian applied the techniques of NMR to imaging, with the goal of distinguishing malignant from benign tumors. Subsequent to these discoveries, Lauterbur produced images of capillary tubes.[8] These discoveries have stimulated the progressive development of MRI to its present state. As a diagnostic technique, MRI has been applied successfully in imaging of the heart,[4,6] brain,[2] spine,[5] peritoneal and retroperitoneal structures,[3] as well as musculoskeletal anatomy and pathoanatomy.[10,15] Previous reports indicate that MRI has been an effective technique for imaging of meniscal, ligamentous, osseous, and articular structures of the knee joint.[9,12-14,18,19,21]

The purpose of this study is to: (1) establish anatomical correlations between multiplanar cadaveric cryosections with corresponding multiplanar MR images; (2) present a successful technique for anatomical study and multiplanar

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MR imaging of the viable human knee; (3) establish pathoanatomical correlations of MRI with arthroscopic surgery; (4) present the use of MRI as a diagnostic test in terms of accuracy, sensitivity, specificity, PPV, and NPV; and (5) present an algorithm of the potential use of MRI in the overall management of traumatic knee injuries.

## MATERIALS AND METHODS

Multiplanar anatomical correlation is provided through a multiplanar cadaveric cryosectioning technique as described by Rauschning et al.[17] First, the lower extremity was amputated above the knee as the femoral artery and vein is injected with a colored plaster mixture. Cadaveric specimens are then deep frozen and transferred to a heavy-duty cryomicrotome stage. The freezing process allowed the soft tissues, cavities, and anatomical structures to maintain their true spatial relationships. Undecalcified frozen specimens were then cryoplaned at 1 micrometer intervals. A specifically designed camera attached to the knife holder allowed sequential photography of the cryoplaned surface without variation in magnification or obliquity. Photographs were taken at 20 micrometer intervals on a Kodachrome 25 ASA color reversal film with a commercial 35 mm single lens reflex equipped with a flat field macrolens and an automated electronic flash unit.[17,19]

Direct anatomical correlation of MR images to cryomicrotomed sections of the same specimen is difficult due to the inherent limitations of imaging nonviable tissues. In fact, this was performed in three specimens, resulting in suboptimal images. In view of this fact, indirect anatomical correlations were established by comparing corresponding cryosections to multiplanar MR images of the normal viable knee joint. All images were obtained on a 0.3-T permanent magnet system (Fonar Beta 300 unit) using a spin-echo pulse sequence (SE/500/28). The knee was extended and externally rotated 20° without the application of stress or distraction. A solenoid surface coil was circumferentially applied to the surface of the knee. Images were obtained on a 256 × 256 matrix and had 4.5 mm thickness with a 0.75 mm pixel size. Coronal, sagittal, and/or axial images were obtained.

Pathoanatomical correlations were established in a clinical setting using arthroscopic evaluation and treatment as the reference point. One hundred five patients with acute and chronic traumatic knee injuries were referred to the UCLA Department of Radiological Sciences for further evaluation. Patients were divided into two populations; the first referrals came from "the specialist" orthopaedic surgeons whose practice was predominantly knee evaluation and treatment. The second population was referred from "general" orthopaedic surgeons who had no concentrated specialty in the knee joint. Each orthopaedic surgeon made a referral clinical judgment and MRI was performed on the respective knee in question.

Adherence to a rigid scientific design was maintained as the MR images of the 105 patients were interpreted in a prospective and retrospective fashion by three radiologists experienced in the interpretation of MR images. Objective criteria were established for ligamentous and meniscal pathology as follows: A meniscus homogenously low in signal was considered to be normal or Grade 1 (see Figs. 1B and 4B). Grade 2 menisci were characterized by small or punctate regions of increased signal (probably normal), Grade 3 were characterized by small linear regions of increased signal or more moderate nonlinear elevated signal regions (probable tears). Menisci with grossly truncated shape or those having regions of increased signal, whether linear or nonlinear were rated as Grade 4 (definite tears). In this study Grades 1 and 2 menisci were considered negative and Grades 3 and 4 menisci were interpreted as tears (see Figs. 7 to 9).

Figures 2B and 3B are MR images of normal cruciate ligaments, indicated by continuities of signal intensity between anatomical origin and insertion, respectively. Objective criteria for the cruciate ligament tears include: (1) lack of continuity of signal and changes in signal intensity in the anatomical regions of the anterior and posterior cruciate ligaments; (2) abnormal femorotibial spatial relationships; and (3) associated injuries. Other pathoanatomical entities, such as quadriceps tendon and patellar tendon rupture, osteochondral fragments, fractures, and traumatic effusion were also imaged. The additional information obtained from the MRI was used by the respective orthopaedic surgeon and therapy was instituted.

Eighty-three patients presented for arthroscopic surgical followup, which proceeded in the usual recommended fashion. Information from the arthroscopic surgery was then correlated with the preoperative clinical judgment, as well as MRI data. Determination of the reliability of clinical judgment versus MRI for the evaluation and treatment of knee pathology was analyzed statistically using five parameters. These included:

(1) *Accuracy.* In a group of patients, what percentage will be correctly classified by the MRI test?

(2) *Sensitivity.* Of the patients who have definite knee pathology, what percent will have positive MRI results?

(3) *Specificity.* Of the patients who did not have knee pathology, what percent of the MRI results will have negative MRI results?

(4) *NPV.* What percentage of the patients who have a negative MRI do *not* have the specific knee pathology?

(5) *PPV.* What percentage of the patients who have a positive MRI result actually have that specific knee pathology?

Those patients who were not arthroscoped and were subjected to only clinical followup comprised a second followup group. These patients were subjectively and objectively evaluated at 3 month and 6 month intervals. Patients were considered to have a positive followup at these interval times if their initial presenting symptoms and physical findings persisted. Followup was considered negative if the patient no longer had significant symptomology.

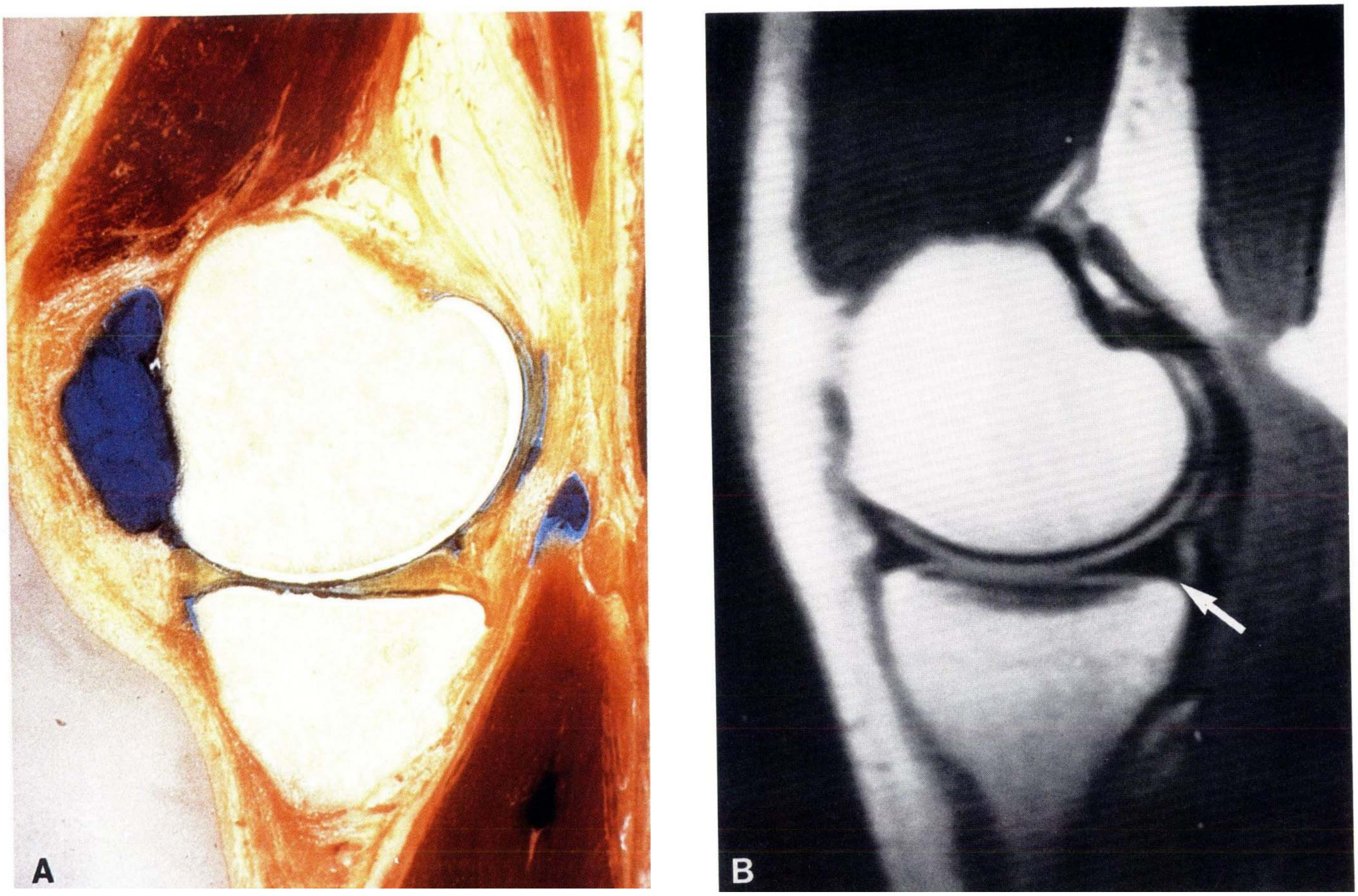


**Figure 1.** Sagittal medial cadaveric cryosection (A) that correlates with corresponding MR image (B). Note the normally homogeneously black area in the medial meniscal region (arrow).

## RESULTS

### Normal anatomy

Figures 1 to 6 present the multiplanar cryosectioned cadaver specimens along with the corresponding MR images of a normal patient in the axial, sagittal, and coronal planes. In the coronal plane, it is possible to define the cruciate ligaments, the medial collateral ligament, the osseous anatomy, and the chondral surfaces. The spatial anatomical relationships can be appreciated as well as the correlations with MR images. The axial plane optimally depicts the posterior neurovascular, musculotendinous structures, and the patellofemoral articulation. It is in this plane that specific patellofemoral measurements of alignment and angular relationships can be made. The sagittal plane is the most effective plane to depict the cruciate ligaments, the menisci, and structures in the anterior and posterior portions of the knee. The clarity and resolution of the MR images is not only correlative with the anatomical structures, but is quite informative, as it reveals other structures, including distal epiphyseal femoral growth plate. In conclusion, the technique of cadaveric multiplanar cryosectioning allowed a unique opportunity to establish multiplanar MRI anatomical correlations with a high degree of reproducibility.

### Pathoanatomical correlation

Eighty-three patients underwent MRI and subsequent arthroscopic surgical followups. These patients had a multitude of traumatic knee pathologies, including medial meniscal tears ($N = 47$), lateral meniscal tears ($N = 16$), anterior cruciate tears ($N = 13$), and posterior cruciate tears ($N = 3$). Other pathologies include osteochondral fragments, patellar and quadriceps tendon lacerations, and osteochondritis dessicans. Figures 7 to 9 and the data in Table 1 summarize the MRI and surgical findings in patients with clinically suspected anterior cruciate tears and lateral meniscal and medial meniscal tears. In an attempt to avoid misconceptions concerning the application of these statistical parameters used, each definition will be illustrated.

*Sensitivity.* There are 16 patients who had an arthroscopically visible lateral meniscal tear and 12 of these were considered a tear by MRI. Therefore, the sensitivity is 12/16, or 75%.

*Specificity.* Sixty-six patients did not have a tear, and 63

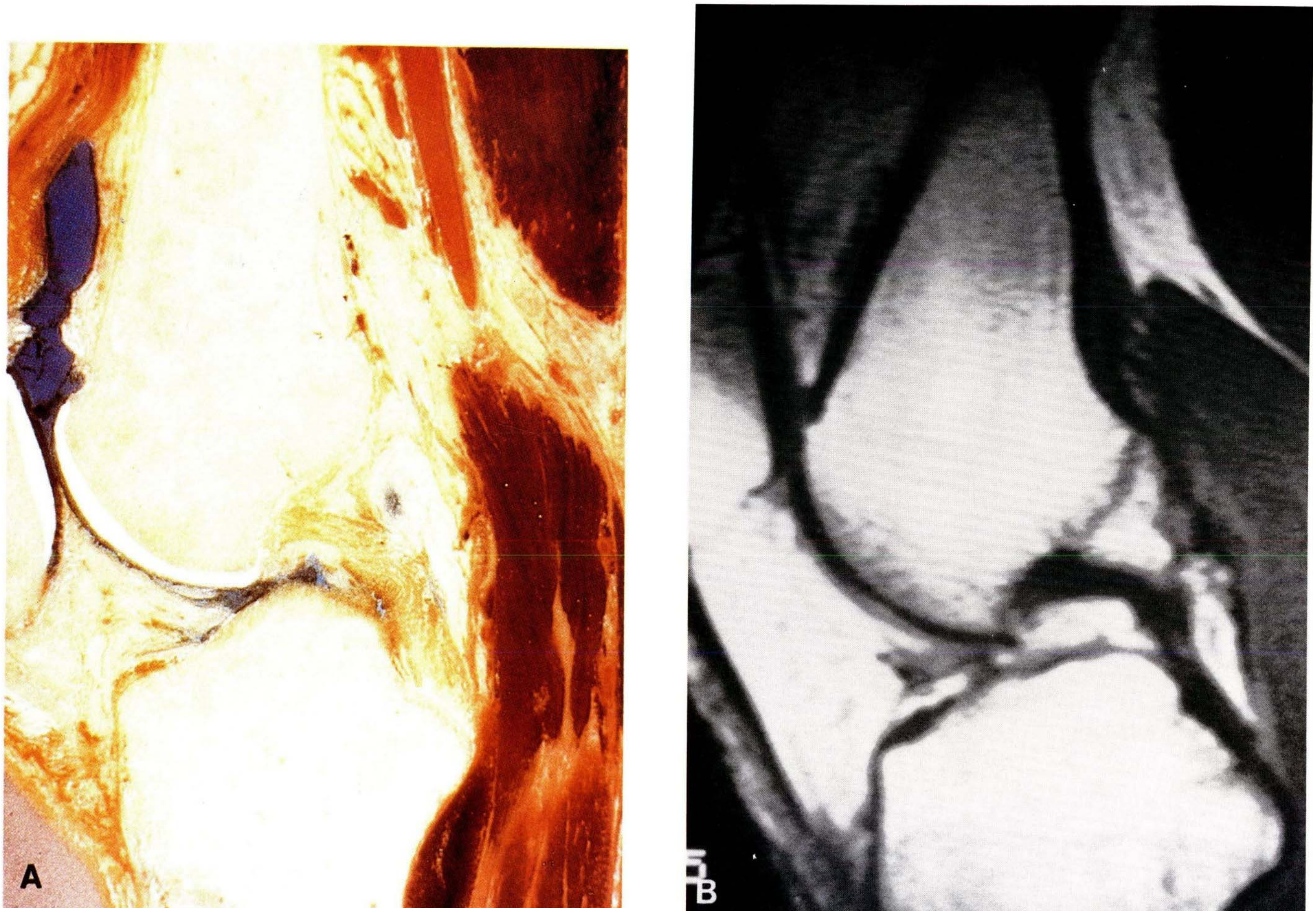


**Figure 2.** Sagittal intercondylar notch cadaveric cryosection (A) that correlates with corresponding MR image (B). Note the signal intensity and continuity in the anatomical region of the normal posterior cruciate ligament.

of these were considered negative by MRI; therefore, the specificity is 63/66 or 95%.

*NPV.* Sixty-seven patients tested negative by MRI. Of these, 63 had no tear; therefore, the NPV is 63/67, or 94%.

*PPV.* Of 15 patients tested MR positive, 12 actually had a torn lateral meniscus. Therefore, the PPV is 12/15, or 80%.

*Accuracy.* Of the 82 patients, 12 + 63 = 75 were correctly classified. Therefore, the accuracy is 75/82, or 91%.

The incidence of medial meniscal tears was 58.8% as compared to 19.5% for the lateral meniscus, a ratio of approximately three to one. Accordingly, for the medial meniscus, the sensitivity was 45/47, or 95.7%; the specificity was 27/33, or 81.8%; the NPV was 27/29, or 93.1%; the PPV was 45/51, or 88.2%; and lastly, the accuracy was 72/80, or 90%.

There was complete agreement with the ACL data (Table 1C). There were 13 patients who had a tear of the ACL and all of these were considered positive by MRI. In addition, 70 patients were determined to be negative by MRI, which determination was correlated with arthroscopic followup. Sensitivity, specificity, PPV, NPV, and accuracy are estimated to be 100%. The incidence of anterior cruciate tears in this study was 13/83, or 15.7%.

The data presented from the 22 patients in whom arthroscopic followup was not obtained is presented. In this subpopulation 17 patients had negative MRI results. All 17 patients had a negative clinical followup; therefore, the MRI had 100% specificity. On the other hand, there were five patients who had persistent clinical symptoms, and thus, a positive clinical followup. Of this group, MRI results were positive in three; this MRI subgroup had a 60% sensitivity. The small numbers in this group make these estimates less reliable.

Table 2 contains data indicating the ability of the clinician to diagnose meniscal tears. In the evaluation of the subpopulation seen by knee "specialists," the sensitivity was determined to be 92%, while the sensitivity for the "generalist" orthopaedic surgeon was 69%. The specialist has an accuracy of 73%, whereas the generalist has an accuracy of 43%. The differences between these groups are statistically significant using the chi square test. It is clear from Table 2A that the general orthopaedic surgeon tends to overcall the incidence of meniscal tears based on clinical examination.

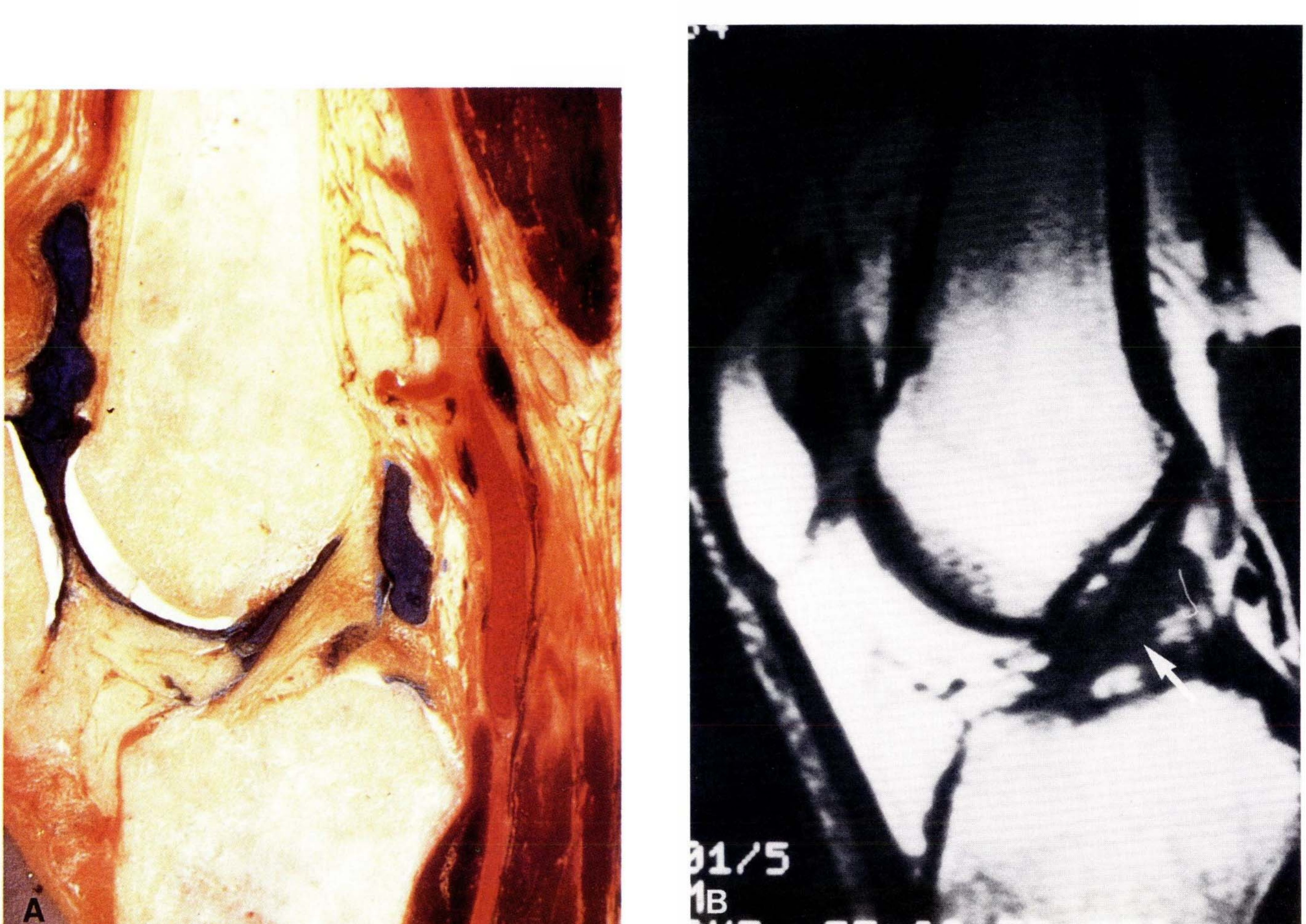


**Figure 3.** Sagittal intercondylar notch cadaveric cryosection (A) that correlates with corresponding MR image (B). Note the signal intensity and continuity of the normal ACL (arrow).

## DISCUSSION

Traumatic knee pathology remains a difficult therapeutic and diagnostic challenge. In the past, the methods of diagnosis were limited to physical examination and film evaluation of standard radiographs. The characterization of soft tissues and ligamentous and meniscal pathology can be limited by these techniques. Arthrography has been used to augment the data base in the evaluation of these injuries.[7,11] Tria et al.[20] analyzed the accuracy, specificity, and sensitivity of arthrography for evaluation of meniscal and cruciate pathology and conclude that this technique's diagnostic efficacy is equivalent to that of physical examination alone.

At earliest inception, arthroscopic surgery was recognized as a diagnostic technique to facilitate the understanding of intraarticular pathology. In recent years, arthroscopic knee surgery has evolved to become an excellent diagnostic and therapeutic tool. Several studies indicate the accuracy of arthroscopy to be between 90% and 95% in the diagnosis of meniscal tears.[7,11] Due to today's improved optical techniques, use of wide angle arthroscopes, and efficient triangulation techniques, these are probably underestimations of arthroscopy's true diagnostic ability. It is for this reason that we have used arthroscopy as our definitive standard reference point with which to compare any other test.

MRI has been used effectively as a tool for evaluation of a multitude of musculoskeletal problems including the spine and hip and, most recently, the shoulder, ankle, and wrist. The purpose of this study is to establish the anatomical and pathoanatomical correlations of MRI and to define the potential role of this technique in the clinical evaluation of traumatic knee injuries.

Using this cryosectioning technique we have demonstrated that, with unique detail, these techniques can accurately define and characterize some of the precise details of the normal anatomical and spatial relationships. In addition, from this multiplanar anatomical study, we have derived specific MR techniques and protocols to better evaluate pathoanatomical changes that are now used in routine clinical practice.

In this study, arthroscopic and clinical followup were used to establish diagnostic accuracy of MRI (Fig. 10). One hundred five patients were studied with a multitude of traumatic pathologies, including lateral and medial meniscal

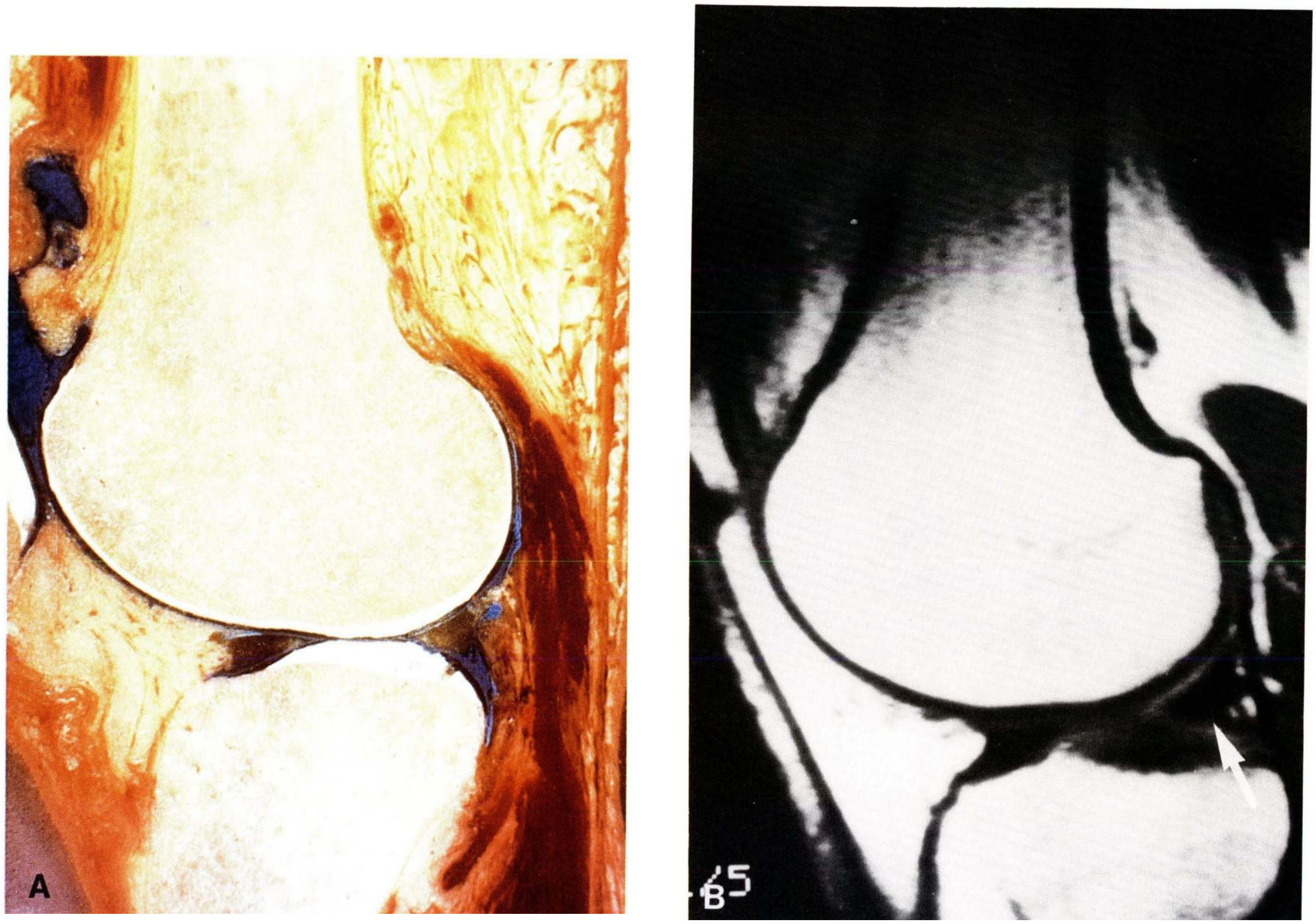


**Figure 4.** Sagittal lateral cadaveric cryosection (A) that correlates with corresponding MR image (B). Note the homogeneously black signal in the area of the normal lateral meniscus (arrow).

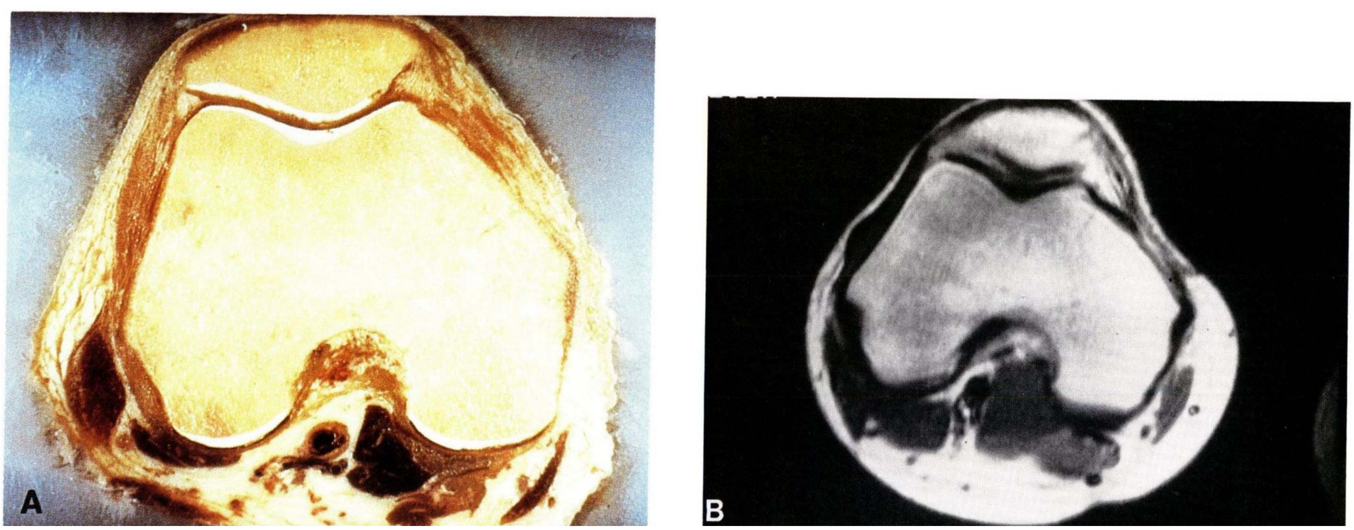


**Figure 5.** Axial cadaveric cryosection (A) that correlates with corresponding MR image (B). Note the patellofemoral articulation and detail of articular surfaces.

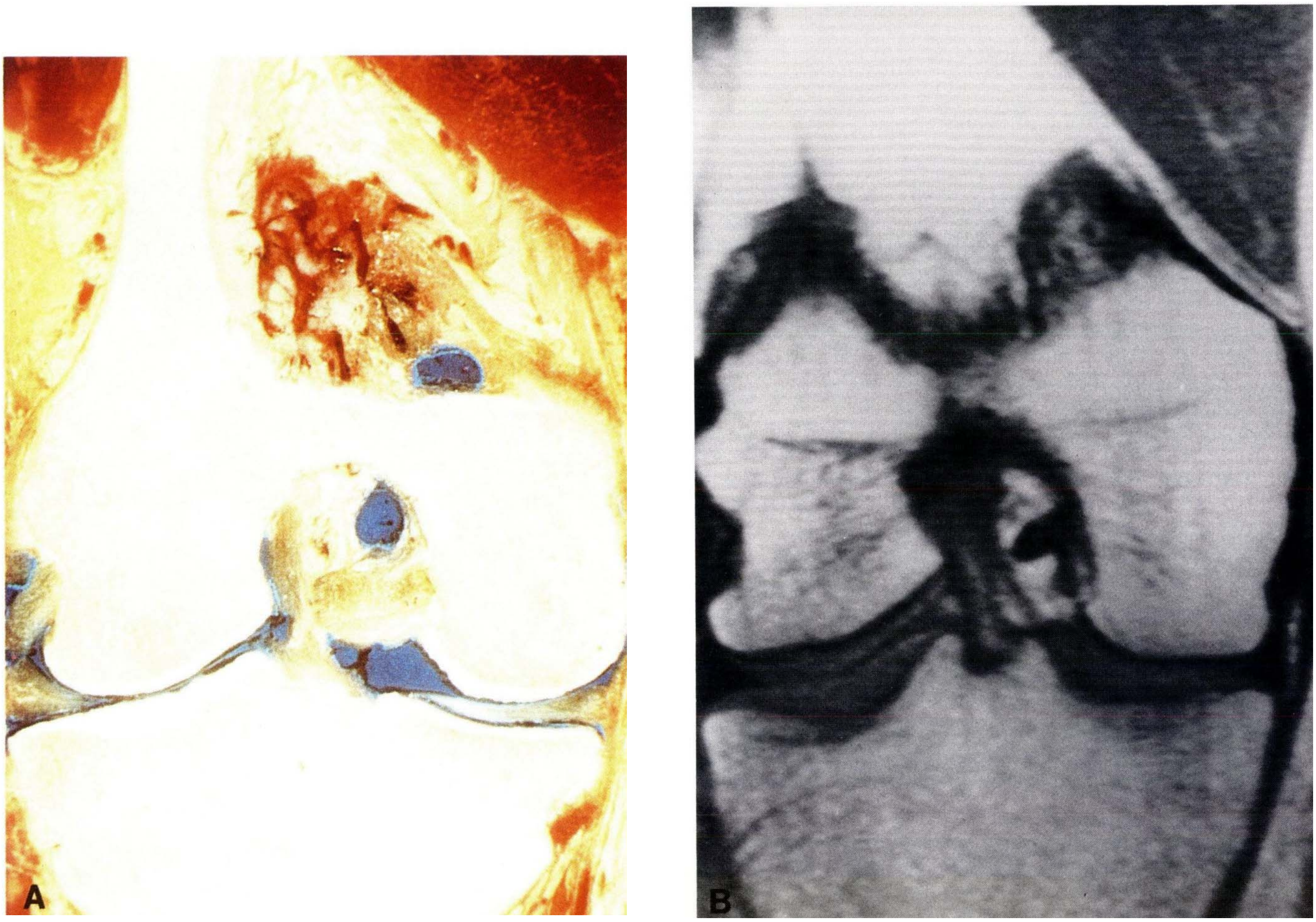


**Figure 6.** Coronal cadaveric cryosection (A) that correlates with corresponding MR image (B). Note the anatomical presence of the anteromedial and posterolateral hands of the ACL. In addition, at this level the medial collateral ligament is well visualized.

tears, anterior and posterior cruciate tears, osteochondral fragments, and fractures. The accuracy for the evaluation of medial and lateral meniscus and anterior cruciate tears was 90%, 91%, and 100%, respectively. The sensitivity or the ability to recognize a pathologic medial meniscus, lateral meniscus, and ACL was 95.7%, 75%, and 100%, respectively. The disparity in these values may be a function of the fact that there were only 16 patients who had a lateral meniscus tear. Thus, this low number may contribute to the statistical disparity between respective estimated sensitivities.

The specificity in the medial meniscus, the lateral meniscus, and ACL is 81.8%, 95%, and 100%, respectively. On closer examination, there are several explanations for the number of false positives seen in the interpretation of the medial meniscus. Occasionally other pathology adjacent to the meniscus was misinterpreted as a meniscal tear. As examples, chondral injuries and cruciate ligament tears contiguous to the posterior portions of the medial meniscus were found retrospectively to correlate with abnormalities seen on MRI which was originally misinterpreted as meniscal pathology. The NPV for the medial and lateral meniscus and ACL was 93.1%, 94%, and 100%, respectively. This facet of the study supports the thesis that if a patient has a negative MRI, then there is a very high probability of having no pathology. PPV for medial and lateral meniscus and ACL was 88.2%, 80%, and 100%, respectively. Once again, this reflects a higher rate of false positives. Further evaluation of this patient population reveals that in several of the early cases, artifact contributed to the false positive misinterpretation when indeed there was no pathology present. The perfect agreement between the MRI and ACL pathology is partly due to the closed and more elaborate examinations of these patients with suspected ACL tears.

There are, and have been, several limitations in the development of MRI techniques. The UCLA experience has been a learning curve such that many of the early images were investigative attempts at correlating anatomy and pathoanatomy. Progressively, the group has defined optimal systematic protocols and techniques for the evaluation of a multitude of traumatic pathologies. As a consequence of these refinements, recent trends indicate a gradual improvement in the reliability of this diagnostic test.

TABLE 1
Surgical findings in patients with tears of the menisci and the ACL.

TABLE 1A
ARTHROSCOPY LATERAL MENISCUS

| | TEAR | NO TEAR | TOTALS |
|---|---|---|---|
| MRI POSITIVE TEAR (3 OR 4) | 12 | 3 | 15 |
| MRI NEGATIVE (1 OR 2) | 4 | 63 | 67 |
| TOTALS | 16 | 66 | 82 |

TABLE 1B
ARTHROSCOPY MEDIAL MENISCUS

| | TEAR | NO TEAR | TOTALS |
|---|---|---|---|
| MRI POSITIVE TEAR (3 OR 4) | 45 | 6 | 51 |
| MRI NEGATIVE (1 OR 2) | 2 | 27 | 29 |
| TOTALS | 47 | 33 | 80 |

TABLE 1C
ARTHROSCOPY ANTERIOR CRUCIATE LIGAMENT

| | TEAR | NO TEAR | TOTALS |
|---|---|---|---|
| MRI ALC TEAR | 13 | 0 | 13 |
| MRI NO ALC TEAR | 0 | 70 | 70 |
| TOTALS | 13 | 70 | 83 |


**Figure 7.** Sagittal medial MR image through abnormal medial meniscus. Note gross distortion of shape and the linear increase in signal in the meniscal region (arrow). This is a Grade 4 medial meniscal tear by MRI that correlated with the arthroscopic finding of a complex tear of the posterior medial meniscus.


**Figure 8.** Sagittal lateral MR image through abnormal lateral meniscus. Note linear region of increased signal in the posterior lateral meniscal region (arrow). This is a Grade 3 lateral meniscal tear by MRI that correlated with the arthroscopic finding of a longitudinal tear in the posterior horn of the lateral meniscus.


**Figure 9.** Sagittal intercondylar notch MR image from a patient with anterolateral rotatory instability. Note the discontinuity of signal and intensity in the anatomical position of the ACL (arrow). Arthroscopy revealed a midsubstance tear of the ACL without meniscal pathology.

Moreover, in approximately 25% of the studies, patient movement may diminish image quality and reproducibility. At the outset of the study our technique was slow, requiring patients to remain still for approximately 1 hour. However,

TABLE 2
Results of evaluations by clinicians.

TABLE 2A
CLINICIAN EVALUATION VS. CLINICAL FOLLOW-UP OR ARTHROSCOPY FOR MEDIAL TEAR

| CLINICAL EVALUATION | | CLINICAL FOLLOW-UP OR ARTHROSCOPY: TEAR | NO TEAR | ACCURACY | SENSITIVITY |
|---|---|---|---|---|---|
| SPECIALIST | TEAR | 7 | 2 | 73 % | 92 % |
| | NO TEAR | 2 | 4 | | |
| GENERALIST | TEAR | 11 | 18 | 43 % | 69 % |
| | NO TEAR | 0 | 3 | | |

TABLE 2B
CLINICAL EVALUATION FOR ACL TEAR VS. ARTHROSCOPY

| CLINICAL EVALUATION | | TEAR | NO TEAR |
|---|---|---|---|
| SPECIALIST | TEAR | 7 | 0 |
| | NO TEAR | 0 | 6 |
| GENERALIST | TEAR | 4 | 1 |
| | NO TEAR | 1 | 16 |

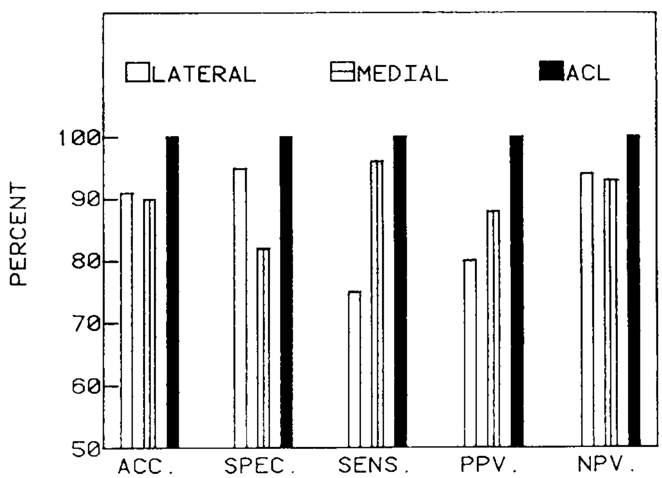


**Figure 10.** This bone graft presents the efficacy of MRI as clinical diagnostic test of knee pathology. The parameters of accuracy (ACC), specificity (SPEC), sensitivity (SENS), positive predictive value (PPV) and negative predictive value (NPV) are presented for tears, ACL, medial and lateral menisci.

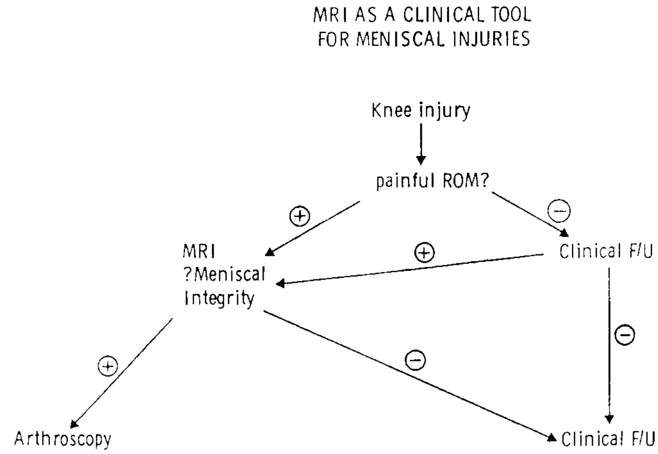


**Figure 11.** Proposed algorithm that suggests the role of MRI in the management of traumatic knee (meniscal) disorders.

with the latest software and imaging techniques, acquisition times have decreased. In addition, we are developing a knee holder to minimize patient movement and image artifact. MRI techniques will undoubtedly become more refined in the future. Other specific technical MR improvements include minimizing image acquisition time, decreasing image interval and slice thickness, and the development of increasingly efficient surface coils.

Based on the excellent results of MRI as applied to these traumatic knee pathologies, we propose an algorithm that conceptually guides the role of MRI in the overall management of traumatic knee disorders. In Figure 12 a patient presents to the orthopaedic surgeon after a traumatic knee injury with a hemarthrosis. A complete history and physical examination establishes the mechanism of injury and an approximation of knee laxity and instability (Figs. 11 and 12). The objective quantitative evaluation of knee laxity is performed with a biomechanical testing technique, such as the KT-1000 arthrometer. If the patient is determined to have functionally, ACL deficient knee with significant laxity and instability, the subsequent question is whether or not the patient is a candidate for surgical repair and/or reconstruction. If so, one can proceed accordingly with respective arthroscopic or open surgical techniques. In this case MR can help define the structural absence of the ACL if this is in question (accuracy, 100%). If the patient is not a candidate for ACL reconstruction and a nonoperative treatment is selected, MRI can effectively define the presence or absence of meniscal pathology and, therefore, obviate the need for arthroscopy as purely a diagnostic tool in patients with normal menisci.

An alternative clinical situation is the patient who presents without significant laxity or instability but has a painful range of motion. The question of meniscal integrity can be effectively answered with MRI (average NPV, 93%; average PPV, 89%). This additional information may be especially important to the "generalist" orthopaedic surgeon in view of his significantly lower diagnostic ability. An additional situation is the patient with mild to moderate knee symptoms and concomitant medial collateral ligament sprain who can be followed progressively, if symptoms persist after medial collateral ligament pain has abated, MR can help define the meniscal pathology and then direct arthroscopic intervention, if appropriate.

In summary, MRI of the knee joint, using a combination of solenoid surface coils[1] and thin-section, high-resolution scanning techniques, is able to depict structural anatomical detail of the knee that correlates well with that seen in cryosectioned cadaveric knees. To date, the resolution of this technique allows a high degree of accuracy, specificity, sensitivity, and positive and negative predictive value when compared to arthroscopic evaluation and clinical followup

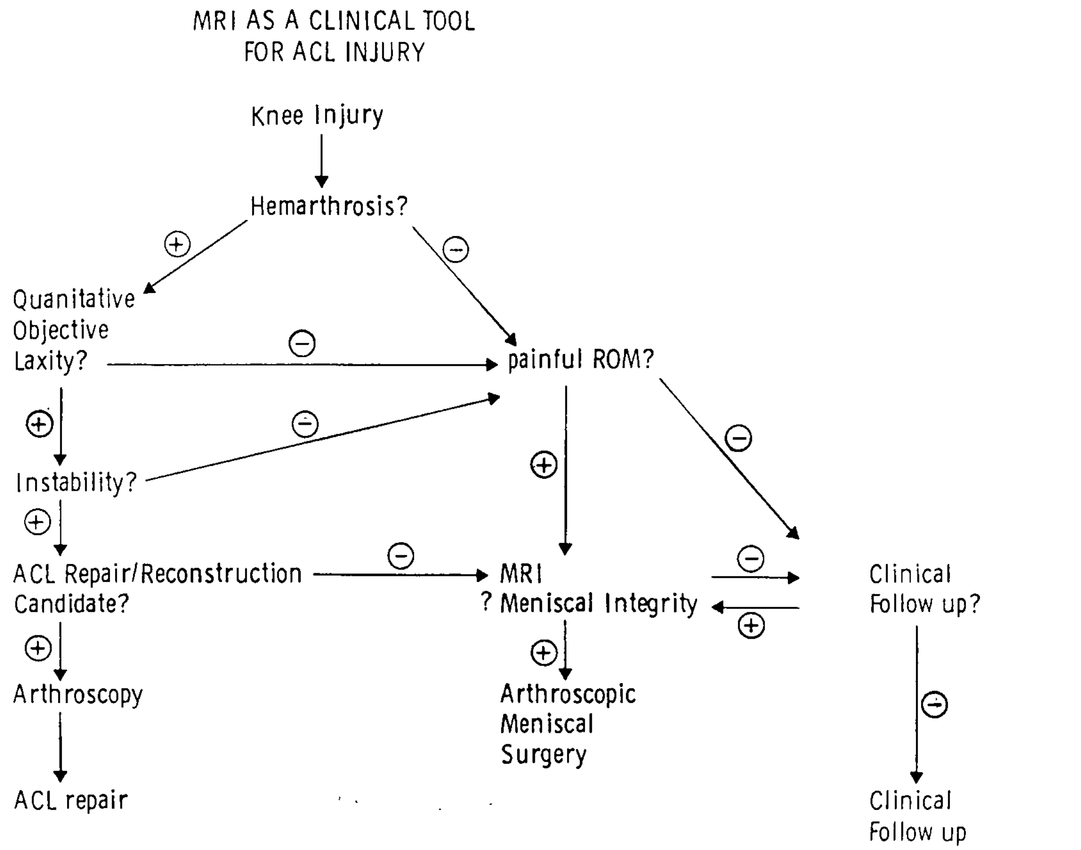


**Figure 12.** Proposed algorithm that suggests the role of MRI in the management of traumatic knee (ACL) injuries.

in the evaluation of traumatic knee injuries. The advantages of MRI techniques include excellent soft tissue contrast, use of no ionized radiation, noninvasiveness, and a multiplanar imaging capability. In addition, MRI is painless and can generally be completed in 30 minutes or less.

In conclusion, this study indicates that MRI, in conjunction with the clinical evaluation of traumatic knee pathology, can contribute to the treatment decision-making process and assist in preoperative planning and postclinical follow-up assessment. Future considerations include a progressive development of MRI techniques that are of higher resolution and quality. As MRI becomes increasingly popular, costs will decrease, thus allowing MRI to become a more commonly used diagnostic test in the evaluation of traumatic knee pathology.

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