Longitudinal Study Comparing Sonographic and MRI Assessments of Acute and Healing Hamstring Injuries

David A. Connell[1]
Michal E. Schneider-Kolsky[1]
Jan Lucas Hoving[2]
Frank Malara[1]
Rachelle Buchbinder[3]
George Koulouris[1]
Frank Burke[1]
Cheryl Bass[1]

OBJECTIVE. We compared sonography and MRI for assessing hamstring injuries in professional football players (Australian football) 3 days, 2 weeks, and 6 weeks after an injury and identified imaging characteristics at baseline that may be useful in predicting the time needed for return to competition.

MATERIALS AND METHODS. Sixty men who are professional football players presented with suspected acute hamstring strain underwent sonography and MRI within 3 days of injury; those who were injured returned 2 and 6 weeks later for follow-up MRI and sonography. Two radiologists interpreted either the MR images or the sonograms and were blinded to the results of the other technique. The following six parameters were measured at each assessment: the muscle injured, the site of injury within the muscle, the longitudinal injury length (expressed in millimeters), the cross-sectional injured area (expressed as a percentage), and the presence of inter- and intramuscular hematoma.

RESULTS. At baseline, MRI identified abnormalities in 42 (70.0%) of 60 patients, whereas sonography found abnormalities in 45 (75%) of 60. At 2 weeks, 29 (59.2%) of 49 scans showed abnormalities on MRI and 25 (51.0%) of 49 showed abnormalities on sonograms. Of those players who were injured at baseline, 15 (35.7%) of 42 and 10 (22.2%) of 45 still showed abnormal results on scans at 6 weeks on MRI and sonography, respectively. However, all but one player had returned to competition. The biceps femoris was the most commonly injured muscle and the musculotendinous junction was the most common site of injury. Injuries appeared significantly larger on MRI than on sonography at all time points. Our analysis showed that at baseline, the longitudinal length of hamstring tear on MRI had the highest statistical correlation with recovery ($r = 0.58$, $p < 0.0001$) and was the best radiologic predictor for return to competition.

CONCLUSION. Sonography is as useful as MRI in depicting acute hamstring injuries and because of lower costs may be the preferred imaging technique. However, MRI is more sensitive for follow-up imaging of healing injuries. The longitudinal length of the strain as measured on MRI is a strong predictor for the amount of time needed until an athlete can return to competition.

Hamstring muscle injury is common in athletes and often results in prolonged rehabilitation and time out from competition [1]. Generous remuneration and desire to play at the professional level intensify the pressure to return to competition rapidly and may undermine the rehabilitation process. However, a premature return to competition may result in recurrent injury and a more prolonged period of convalescence [2–4]. Characterizing the severity of muscle injury is important in guiding rehabilitation.

Research directed toward identifying prognostic factors that may guide the rehabilitation process after hamstring strains has been limited. It is generally accepted that a previous hamstring strain and age are strongly associated with increased risk for reinjury [5, 6]. A recent MRI study showed that time lost from competition was related to the percentage of the abnormal muscle area and the volume of muscle injury [4, 7]. A retrospective study in a small group of athletes identified complete muscle rupture, hemorrhage, fluid collections, and distal myotendinous involvement as possible but poor and inaccurate prognostic factors [4].

Sonography has been the front-line technique for investigating hamstring strains in the acute setting at our institution because of its accessibility and cost. More recently, clinicians have turned to MRI to evaluate hamstring healing and repair before athletes return to competition [8–10]. However, little information is currently available to show that MRI

Received January 8, 2004; accepted after revision April 26, 2004.

[1]Department of Medical Imaging, Victoria House Hospital, 316 Malvern Rd., Prahran 3181, Australia. Address correspondence to D. A. Connell.

[2]Department of Epidemiology and Preventive Medicine, Monash University, Cabrini Hospital, Melbourne, Victoria 3144, Australia.

[3]Department of Clinical Epidemiology, Monash University, Cabrini Hospital, Melbourne, Victoria 3144, Australia.

AJR 2004;183:975–984

0361–803X/04/1834–975

is superior to sonography in describing muscle injury, and to our knowledge, no study to date has investigated the type of and duration of changes in hamstring muscle damage observed during the healing phases.

The aim of this study was to compare the characteristics of sonography with MRI in assessing both the acute and healing phases of hamstring injuries. We also investigated whether MRI and sonography characteristics identified at baseline could serve as clinically useful prognostic factors for the return to full competition of professional football players (Australian football).

Materials and Methods

Recruitment of Subjects and Selection Criteria

Between February and August 2002, 61 professional male Australian football players with suspected acute hamstring injury sustained either during training or during competition were asked by the club physician to participate in the study. Sixty agreed to participate. One player refused to participate because of an inability to comply with the follow-up assessments. Within 3 days of injury, the players were scheduled for an appointment at our imaging center where an investigator assessed each player's eligibility for the study. Players were included if their symptoms were acute onset of posterior thigh pain or stiffness and if they were unable to complete their training session or game. Players were excluded if they had either a chronic or an ongoing hamstring injury at the time of presentation at the clinic; were unwilling to comply with follow-up; or had contraindications to MRI, including severe claustrophobia, intracranial aneurysm clips, pacemakers, or foreign metallic objects. Furthermore, players identified during imaging as having complete tears of the hamstring muscles requiring surgical repair were excluded from the study. The study protocol was approved by the human research ethics committee affiliated with our clinic, and all players gave informed consent.

Data Collection

Two radiologists, each having more than 7 years of experience in musculoskeletal radiology, interpreted the results from each imaging technique and scored the abnormal characteristics according to a prespecified score sheet. Sonography was initiated by a technologist and completed by the radiologists. Each pair of radiologists reached a consensus agreement on one imaging technique while being blinded to the findings of the other technique. The players underwent repeated examinations 2 and 6 weeks later if an abnormality was identified on either technique. The two radiologists used the same outcome measures on the repeat visits. Players who presented without radiologic evidence of injury on sonography or MRI were not rescanned using that particular technique. Only the baseline scanning results were reported to the club doctors. Subsequent assessments were withheld to avoid player management bias.

MRI

The players were positioned prone on the table and examined using a 1.5-T superconducting unit (Sigma LX, GE Healthcare). A phased-array surface coil (Shoulder Array, Medrad) was strapped over the thigh and centered over the region of maximal tenderness as identified by the player. A coronal localizing image was obtained followed by these sequences: axial and coronal oblique fast spin-echo imaging along the longitudinal axis of the hamstring complex (TR/TE_{eff}, 4,000/45) with a 512 × 384 matrix, 2 signals acquired, 20-cm field of view, 5-mm section thickness with no gap, and echo-train length of 8–12. Axial and coronal oblique fast spin-echo inversion recovery imaging was performed along the longitudinal axis of the hamstring complex (TR range/TE range, 5,000–6,500/35–55; inversion time, 120 msec) with a 256 × 224 matrix, 2 signals acquired, 20-cm field of view, and 5-mm section thickness with no gap.

Sonography

Sonography was performed using an HDI 5000 unit (ATL), a linear 12-5–MHz transducer, and one or two focal zones. Players were positioned prone on the table, and the injury site was identified by the area of maximal tenderness. The muscles were evaluated with respect to echogenicity and fiber disruption. The echogenic "sheen" that is frequently seen in the muscles of fit individuals, particularly after recent exertion, was identified to avoid confusion with muscle edema. Edema or hemorrhage was diagnosed on the basis of the presence of an area of increased echogenicity with or without muscle fiber disruption visible in orthogonal planes. In the acute setting, edema and hemorrhage cannot easily be distinguished. Hypoechoic fluid tracking around the outside of the muscle along the fascial layer was considered to be intermuscular hematoma.

All three hamstring muscles were scanned from the ischial tuberosity to the knee joint in both the longitudinal and transverse planes, and the injured area subsequently was scored according to the parameters described in the next section of this article.

MRI and Sonographic Outcome Parameters Measured

During both MRI and sonography, the injured area was identified and the following six radiologic items were assessed: injured muscles, sites of injury within the muscle unit, injured area (a percentage of the cross section), length of injured area (expressed in millimeters), and presence of intermuscular or intramuscular hematoma (collection of focal fluid with abnormal signal intensity or echotexture). The degree of intermuscular hematoma was graded as absent, mild (< 2 cm^2), moderate (< 6 cm^2), large (> 6 cm^2), or absorbed, and the intramuscular hematoma was measured in three dimensions and recorded as total volume. An acute injury was considered to be present if abnormal signal intensity or echotexture could be detected by the radiologists on either sonography or MRI. The description is based on our previous method of interpreting hamstring injuries [11, 12]. On sonography, the percentage of injured muscle in cross section was measured using the area function on the sonographic machine. The ratio between the area of the maximal abnormality and the area of the entire muscle at the same level was used to obtain the percentage of cross-sectional area of muscle damage or fluid collection. If more than one muscle was injured, the muscle with the greater area of signal or echotexture abnormality was considered the primary site of injury and assessment criteria were taken for that particular muscle. Details regarding the players' progress toward returning to full training and play were collected via a questionnaire sent to the treating club physiotherapist. The number of days from the initial injury until return to competition (completed game) was used as the reference for successful recovery of the player.

Statistical Analyses

The number of normal and abnormal findings on MRI and sonography at baseline, 2 weeks, and 6 weeks were summarized in a 2 × 2 table and agreement between the two techniques was assessed using the kappa statistic. The concordance between MRI and sonography was analyzed using chi-square tests. A priori, we defined kappa values of less than 0.20 as poor, between 0.21 and 0.40 as fair, 0.41–0.60 as moderate, 0.61–0.80 as good, and 0.81–1.00 as very good [11]. Players were not rescanned during follow-up if their previous scans showed normal findings. These players remained in the study, but their MRI and sonography parameters were recorded as either zero (cross-sectional area, longitudinal length) or as absent (location, site of injury, presence of hematoma).

In addition, we compared specific MRI and sonography characteristics of the injuries at baseline, after 2 weeks, and after 6 weeks. Differences in the continuous variables between MRI and sonography were analyzed using Wilcoxon's signed rank test. Differences in proportions were compared using McNemar tests for related samples. A few comparisons were not performed because of the low incidence of some characteristics.

The relationship between the time needed to return to competition (measured in days) and the six potential prognostic indicators identified on MRI

TABLE 1 Demographics of 60 Professional Football Players Who Presented with a Suspected Hamstring Injury

Characteristic	Value	SD
Median age (yr)	24	3.8
Mean height (cm)	186	6.0
Mean weight (kg)	88	8.6
Injury	**No.**	**%**
Right hamstring	32	53.3
Dominant (kicking) leg	35	58.3
Hamstring (> 1 yr earlier)	34	56.7
Anterior cruciate ligament graft (previously)	8	13.3

and sonography at baseline were individually evaluated using univariate linear regression analyses. Subsequently, multiple regression analyses were carried out (forward step, $p = 0.05$) for MRI and sonography separately. All analyses were performed using version 11.5 of SPSS (Statistical Package for the Social Sciences) for Windows (Microsoft).

Results

Sixty-one players who were referred to the clinic with a suspected clinical diagnosis of acute hamstring strain were invited to participate in the study. One player refused to participate because of other professional commitments. Thus, 60 players were enrolled in the study. Forty-nine and 31 players presented for their 2- and 6-week assessments, respectively. Reasons for loss to follow-up were mainly due to the players' busy training schedule and frequent interstate travel.

Just before the end of the 6-week follow-up period, six players had a reinjury of the hamstring (pain or stiffness in the posterior thigh and inability to continue athletic activity). The 6-week follow-up scans of these players were not included in the analyses. We were able to retrieve these data for all 60 players enrolled in the study because we collected the return-to-competition data through the club physiotherapists.

The median time from injury until examination was 2.0 days (range, 0–3 days). The demographic details of all players are shown in Table 1. The median age was 24 years (range, 17–33 years). Thirty-two (53.3%) of the 60 players reported hamstring injuries during previous seasons. The number of days to return to full play for all players ranged between 4 and 56 days, with a median duration of 21 days. Twenty-three players (38.3%) returned to competition before the 2-week assessment, 35 players (58.3%) between the 2- and 6-week assessment, and only two (3.3%) took longer than 6 weeks to return to competition.

Comparison Between Abnormal Findings on MRI and Sonography

A comparison between the number of abnormal and normal findings on MRI and sonography at baseline and during follow-up is shown in Table 2. Only players with both complete MRI and sonographic data are included, which explains the lower numbers in the cross-table at 2 weeks (49 players) and 6 weeks (31 players).

A comparison between the number of players showing abnormal or normal findings on MRI and sonography at baseline and 2 and 6 weeks is outlined in Table 2. At baseline, MRI identified radiologic abnormalities in 42 (70.0%) of 60 patients, whereas sonography identified abnormalities in 45 (75%) of 60. Five (11.9%) of 42 patients were found to have abnormal findings on MRI that were not detected sonographically, and eight (17.8%) of 45 patients showed abnormal findings on sonography that were not detected on MRI. Clinically normal scans on both MRI and sonography were documented in 10 (16.7%) of the 60 players, despite a clinical suspicion of hamstring strain. The median time for these players to return to competition was 7 days (range, 7–14 days).

At the 2-week assessment, 29 (59.2%) of 49 scans appeared abnormal on MRI and 25 (51.0%) of 49 appeared abnormal on sonography. Of the 29 abnormal MRI findings, 10

TABLE 2 Findings on MRI and Sonography at Baseline and at 2- and 6-Week Follow-Ups, with Kappa Statistics

Sonography	MRI			κ
	Abnormal	Normal	Total	
Baseline				
Abnormal	36	9	45	
Normal	6	9	15	
Total	42	18	60	0.45
2 Weeks				
Abnormal	19	6	25	
Normal	10	14	24	
Total	29	20	49	0.34
6 Weeks				
Abnormal	8	2	10	
Normal	5	16	21	
Total	13	18	31	0.52

Note.—Data are numbers of players.

TABLE 3 Location and Characteristics of Hamstring Injuries Assessed at Baseline Using MRI and Sonography

Injuries	MRI		Sonography		p
	No.	%	No.	%	
Muscle injured					
Biceps femoris	35	83.3	29	64.4	0.61
Semitendinosus	2	4.8	10	22.2	0.04
Semimembranosus	3	7.1	4	8.9	1.00
> 1 muscle	2	4.8	2	4.4	NA
Site of injury					
Musculotendinous junction	22	52.4	28	62.2	0.33
Myofascial	15	35.7	14	31.1	1.00
Tendon at bone	3	7.1	1	2.2	0.50
> 1 site	2	4.8	2	4.4	NA
Type of injury					
Intermuscular hematoma	26	43.3	6	10.0	< 0.001
Intramuscular hematoma	6	10.0	22	36.7	0.002
Total no. recruited	60		60		
Pathology confirmed	42	70.0	45	75.0	NA
	Median	Interquartile Range	Median	Interquartile Range	
Cross-sectional area injured (%)	10.0	0–20	5.0	1–10	0.01
Length of injury (mm)	60.0	0–100	25.0	2–50	< 0.001

Note.—NA indicates that sample size was too small to compute p.

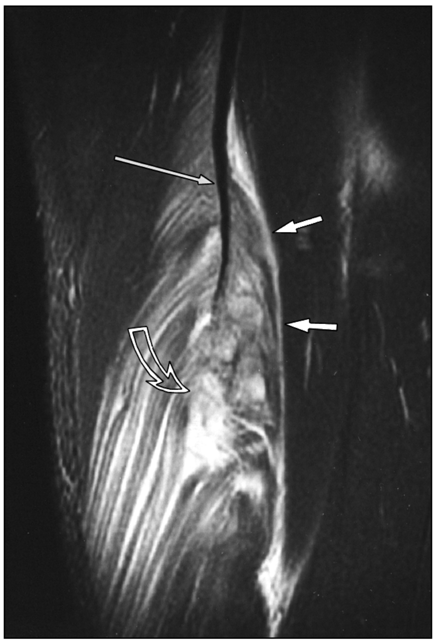
(34.5%) looked normal on sonography, whereas six (24%) of the 25 abnormal findings on sonography looked normal on MRI.

At 6 weeks after injury, 15 (48.4%) of 31 players presenting for imaging still showed radiologic abnormalities on MRI. The corresponding figure for sonography was 10 (32.3%) of 31. Five of the 13 injuries identified on MRI were not detected on sonography and two (20.0%) of the 10 injuries identified on sonography were not detected on MRI. Six players reinjured the same hamstring muscle between their 2- and 6-week assessments. Only the details about their first injury were used for analysis.

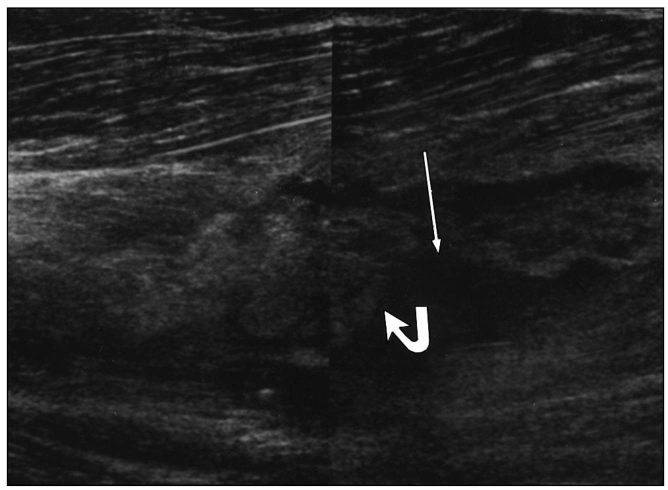
We found moderate agreement between the pairs of radiologists who rated the MR images and sonograms, with kappa values ranging between 0.45 (baseline) and 0.34 (at 2 weeks) and 0.52 (at 6 weeks). Differences in proportions of abnormal findings between sonography and MRI were not statistically significant (McNemar test, all $p > 0.05$ for baseline; 2 and 6 weeks, not shown).

Injury Assessment at Baseline and Follow-Up

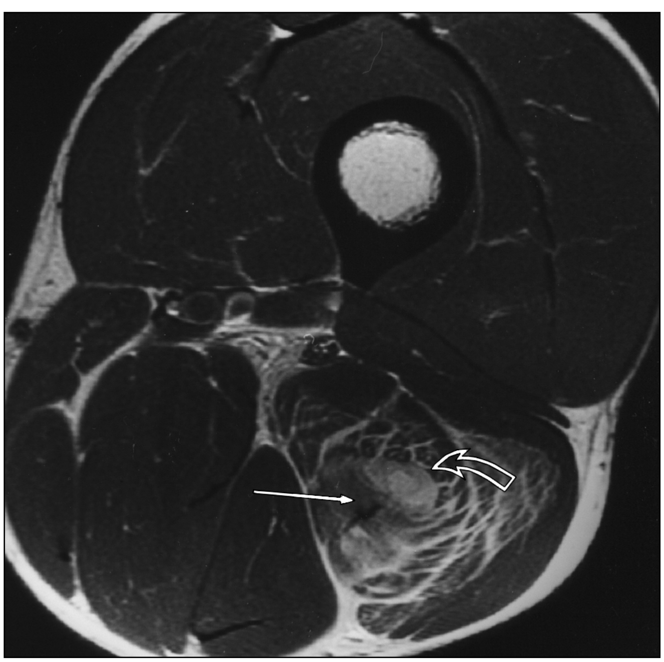
Baseline characteristics of hamstring injuries as identified on MRI and sonography are summarized in Table 3. Among those players identified on imaging as having an acute injury at baseline, the biceps femoris was the



A



B



C

Fig. 1.—Rupture of intramuscular tendon in 28-year-old male professional football player (Australian football).
A, Coronal MR image shows disruption of central tendon (*long solid arrow*) in middle third of biceps tendon (*open arrow*) with hematoma tracking between disrupted fibrils. Fluid signal intensity tracks around epimysial boundary (*short solid arrows*).
B, Correlative longitudinal sonographic image shows disruption of central tendon (*straight arrow*) of torn biceps tendon and hematoma tracks (*curved arrow*) between torn muscle fibers.
C, Axial MR image shows torn retracted central tendon (*straight arrow*) with small pocket of intramuscular hematoma (*curved arrow*) lying adjacent and fluid signal tracks between muscle bundle.

most commonly affected hamstring muscle on both MRI and sonography (35/42 patients [83.3%] and 29/45 patients [64.4%], respectively). The semitendinosus muscle was involved in two (4.8%) of 42 MR images and in 10 (22.2%) of 45 sonograms. Of those 10 sonographic presentations identifying the semitendinosus muscle as the site of injury, MRI did not detect abnormalities in five patients and attributed the injury to the biceps femoris muscle in another five. The semimembranosus muscle was depicted in three (7.1%) of 42 patients on MRI and in four (8.9%) of 45 patients on sonography. Tandem injuries involving two or three muscles of the hamstring complex were seen in two patients each on MRI and sonography.

The musculotendinous junction was the injury site most commonly identified on MRI (22/42 patients [52.4%]) and on sonography (28/45 patients [62.2%]) at baseline. The myofascial covering of the epimysium was involved in 15 (35.7%) of 42 patients on MRI and in 14 (31.1%) of 45 patients on sonography. Examples of injury to the musculotendinous junction as observed on MRI and sonography are shown in Figures 1–3, and an injury involving the epimysial covering is shown in Figure 4. At the 2- and 6-week follow-ups, the individual muscle involvement and injury sites as documented on MRI and sonography were similar to the ones described at baseline.

Description of Injuries

Table 4 outlines the changes of injury characteristics from baseline and during follow-up.

The median cross-sectional area of the injuries—described as the percentage of cross-sectional area showing abnormal signal intensity or echotexture in axial views—appeared significantly larger on MRI than on sonography at baseline and at the 2-week follow-up (p = 0.01 and 0.04, respectively). At the 6-week follow-up, the median injured area as seen in

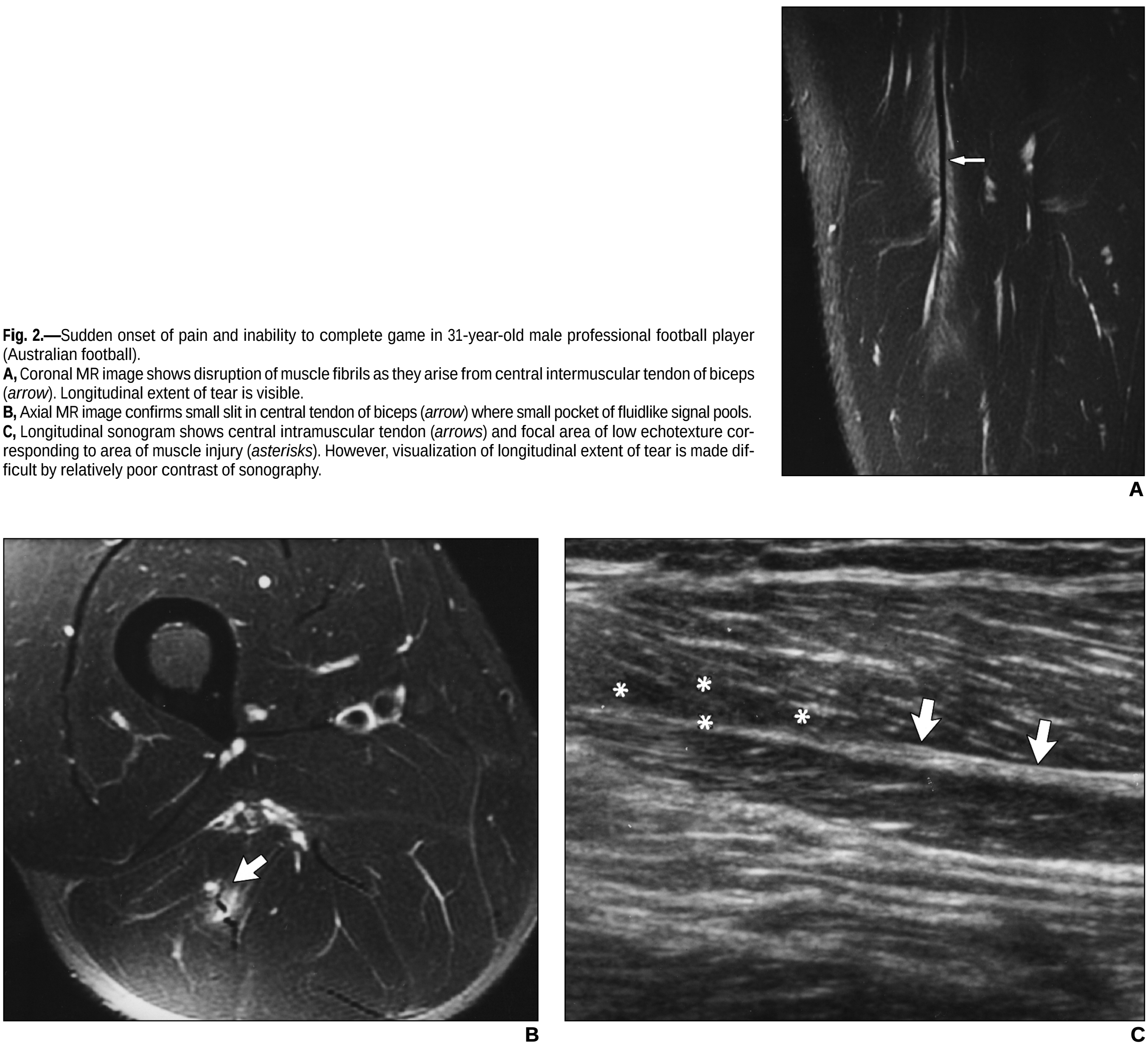


Fig. 2.—Sudden onset of pain and inability to complete game in 31-year-old male professional football player (Australian football).
A, Coronal MR image shows disruption of muscle fibrils as they arise from central intermuscular tendon of biceps (*arrow*). Longitudinal extent of tear is visible.
B, Axial MR image confirms small slit in central tendon of biceps (*arrow*) where small pocket of fluidlike signal pools.
C, Longitudinal sonogram shows central intramuscular tendon (*arrows*) and focal area of low echotexture corresponding to area of muscle injury (*asterisks*). However, visualization of longitudinal extent of tear is made difficult by relatively poor contrast of sonography.

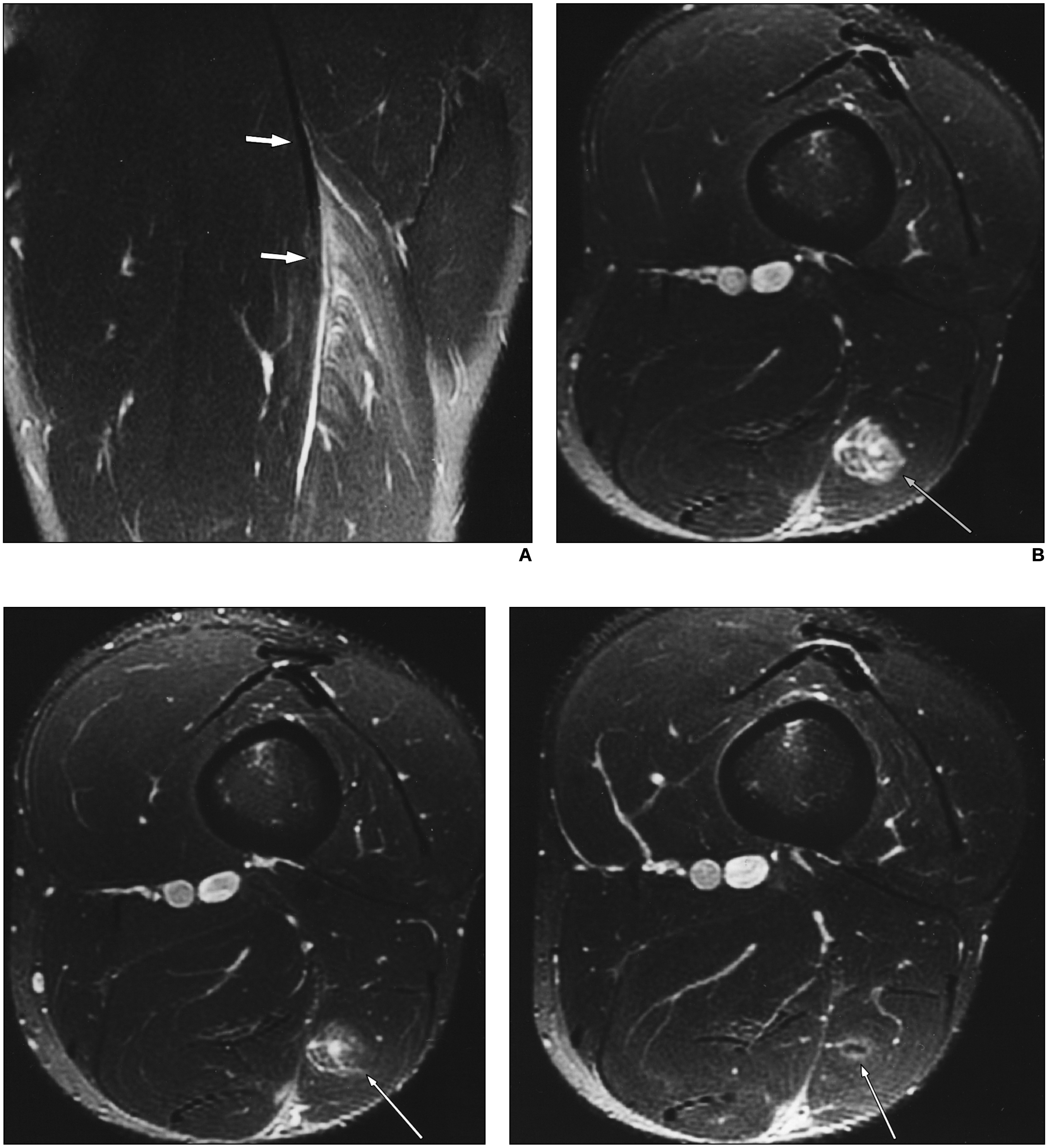


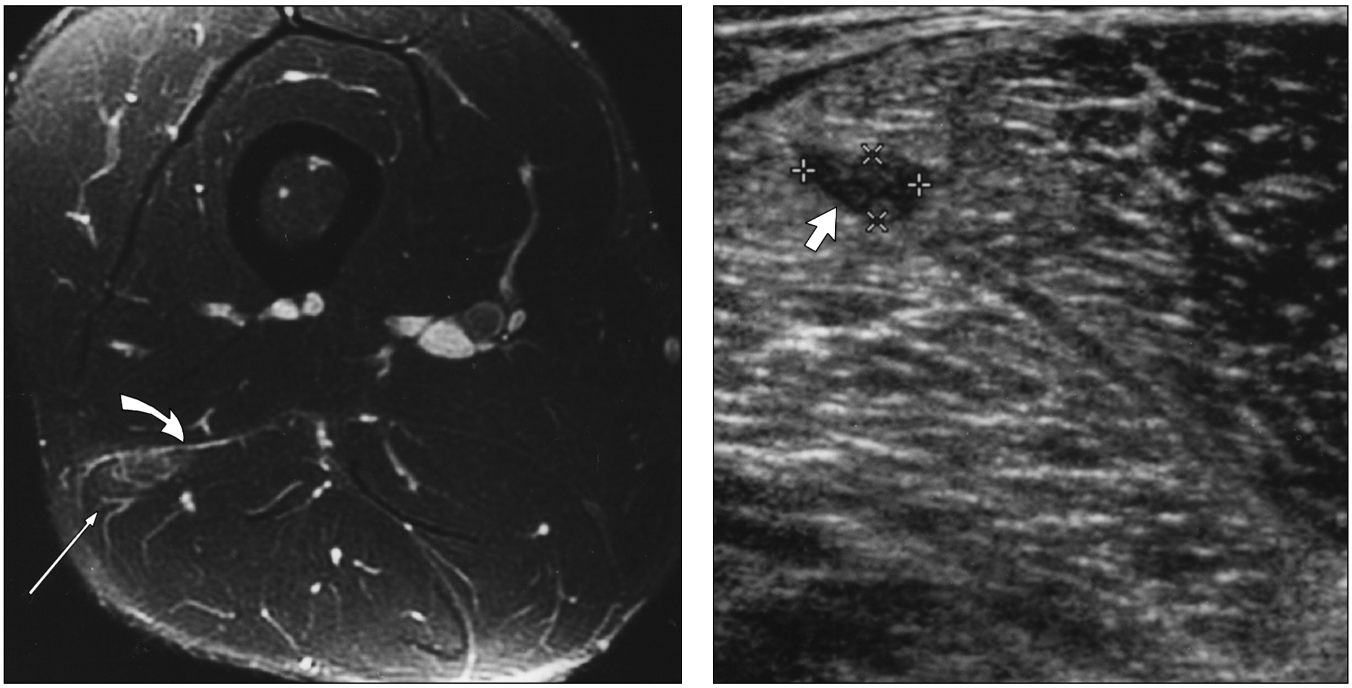
Fig. 3.—Moderate-grade strain injury in 23-year-old male professional football player (Australian football) in upper third of thigh.
A, Coronal MR image shows tearing (*arrows*) of muscle fibers along central tendon of biceps. Longitudinal extent of tear is easily measured on coronal image.
B, Axial MR image obtained at baseline can be used to estimate cross-sectional area of injury with fluidlike signal (*arrow*) tracking into and around muscle fibers.
C, Axial MR image obtained at 2-week follow-up shows incomplete resolution of fluid signal (*arrow*) tracking into and around torn central tendon.
D, Axial MR image obtained at 6-week follow-up shows that high signal intensity has mostly been replaced by focus of low signal (*arrow*) corresponding to fibrosis.

cross-section was 0 on both imaging techniques because most players had no or minimal damage visible on imaging. Similar findings appeared when the length of the injuries was measured. On MRI, length measurements were consistently longer than those on sonography at baseline and at 2 weeks ($p < 0.001$ for both time points).

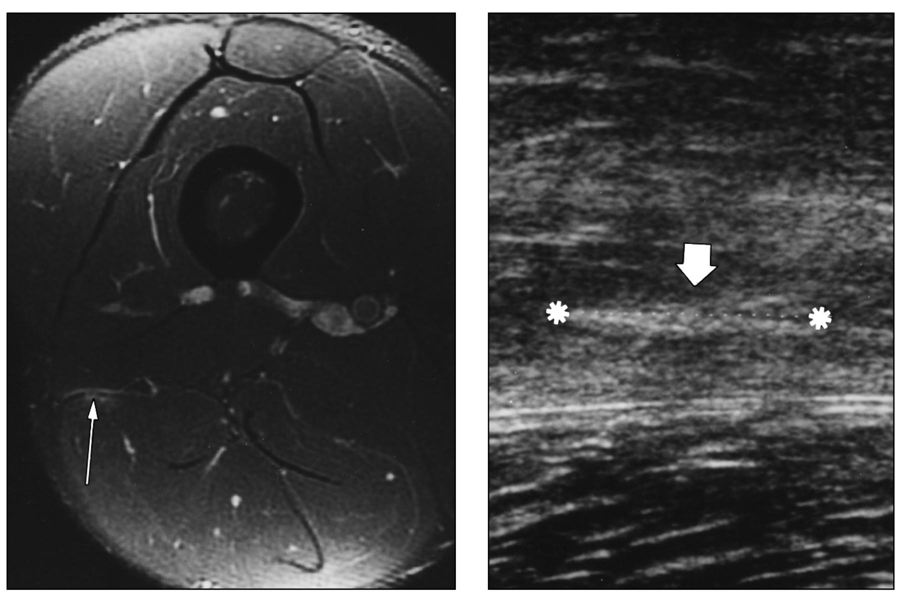
Overall, using both MRI and sonography, the extent of reported injuries (cross-sectional and length measurements) decreased significantly in size during the 6-week assessment period ($p < 0.001$ for cross-sectional injured area and injury length). Changes in radiologic findings of injured biceps femoris muscle as observed on MRI and sonography at baseline, 2-week, and 6-week follow-ups are shown in Figures 3 and 4.

Comparative Predictive Values of Radiologic Assessment Criteria

Univariate analyses showed that for MRI the presence of an injury in the biceps femoris muscle, the cross-sectional injury area (as a percentage score), the length of the injury on MRI, and injury outside of the musculotendinous junction were independently associated with increased recovery time ($p < 0.05$). The best prognostic indicator for MRI was the longitudinal length of the injury ($p < 0.001$) (Fig. 5). Spearman's rank order correlation (r) between the two variables was 0.58 ($p < 0.001$). For sonography, the same indicators were identified as for MRI, but with



A B



C D

Fig. 4.—Epimysial strain at boundary of long head of biceps with short head of biceps in 24-year-old male professional football player (Australian football).
A, Axial MR image shows focal area of abnormal signal (*straight arrow*) is predominantly affecting long head of biceps. Small amount of high signal (*curved arrow*) tracks between intermuscular covering in keeping with fluid or hematoma.
B, Sonogram corresponding to **A** shows focal area of low echotexture (*cursors*) on epimysial boundary corresponding to tear (*arrow*).
C, Axial MR image shows minimal residual high signal (*arrow*) at epimysial boundary.
D, Longitudinal sonogram shows linear band of increased echogenicity (*asterisks*) corresponding to site of epimysial injury (*arrow*) at 6-week follow-up. Note change in sonographic appearance from baseline to 6-week image.

TABLE 4 Injury Characteristics Assessed on MRI and Sonography at Baseline and at 2-Week and 6-Week Follow-Ups

Characteristic Assessed	MRI		Sonography		p[a]
	Median	Range	Median	Range	
Cross-sectional area (%)					
Baseline (n = 60)	10.0	7.5–30.0	5.0	5.0–11.2	0.01
2 Weeks (n = 49)	5.0	0.0–50.0	1.0	0.0–50.0	0.04
6 Weeks (n = 31)	0.0	0.0–35.0	0.0	0.0–25.0	0.06
Length (mm)					
Baseline (n = 60)	60.0	0.0–100.0[b]	25.0	2.0–50.0[b]	< 0.001
2 Weeks (n = 49)	45.0	0.0–210.0[b]	9.0	0.0–150.0[b]	< 0.001
6 Weeks (n = 31)	0.0	0.0–130.0[b]	0.0	0.0–100.0[b]	0.03
	No.	%	No.	%	
Intermuscular hematoma					
Baseline (n = 60)	26/60	43.3	6/60	10.0	< 0.001
2 Weeks (n = 49)	11/49	22.4	4/49	8.2	0.13
6 Weeks (n = 31)	1/31	3.2	1/31	3.2	NA
Intramuscular hematoma					
Baseline (n = 60)	6/60	10.0	22/60	36.7	0.002
2 Weeks (n = 49)	2/49	4.1	14/49	28.6	0.004
6 Weeks (n = 31)	0/31	0.0	5/31	16.1	NA

Note.—NA indicates that sample size was too small to compute p.
[a]Differences between MRI and sonography tested using Wilcoxon's signed rank test (continuous data) or McNemar test for two related samples (dichotomous data).
[b]Interquartile range.

the addition of intermuscular hematoma, which was also associated with increased recovery time ($p < 0.05$).

Multivariate analyses identified a model for MRI and sonography indicators associated with delayed recovery. Because the cross-sectional area and the length of the injury were both highly correlated for MRI ($r = 0.87$, $p < 0.001$) and sonography ($r = 0.69$, $p < 0.001$), only the strongest indicators were chosen in the model. The final model for MRI included the presence of the injury at the biceps femoris muscle ($p = 0.049$) and the length of the injury ($p = 0.001$) (adjusted $R^2 = 37.9\%$). For sonography, the model included the presence of the injury at the biceps femoris muscle ($p = 0.01$), the cross-sectional area of the injury ($p = 0.005$), and the presence of intermuscular hematoma ($p = 0.01$) (adjusted $R^2 = 33.8\%$).

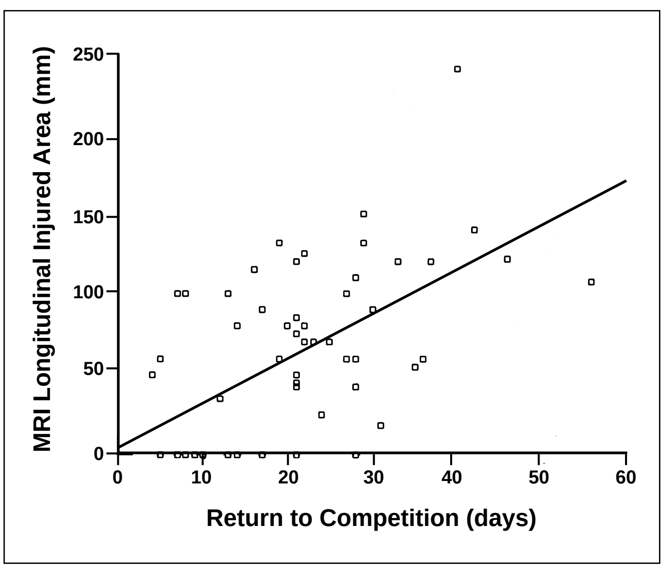


Fig. 5.—Scatterplot and line of best fit depict correlation between longitudinal length of injury as seen on MRI and number of days until return to competition. Spearman's rank order correlation coefficient was 0.58.

Discussion

In Australian football, hamstring strains have been the most common type of injury over the past 10 years, resulting in the highest number of days lost to play during the season [14]. Imaging of the injury has become increasingly relevant for the correct diagnosis and optimal rehabilitation of the players. To our knowledge, this study is the first to directly compare sonography and MRI and to evaluate hamstring strains not only in the acute phase, but also during healing in the subsequent weeks.

We found that MRI and sonography are equally useful for identifying hamstring injuries at baseline, with both techniques confirming the presence of an acute injury in most cases. The extent of the injuries was consistently larger on MRI than on sonography, both in cross-sectional and longitudinal views. However, this discrepancy was due to the increased sensitivity of MRI in showing subtle edema.

In a number of cases, the two techniques were not in agreement regarding the presence of an acute injury. Therefore, after analysis, all cases with discordant findings between MRI and sonography at baseline were reviewed by the radiologists. Those scans indicating an injury on MRI but no abnormality on sonography typically showed subtle hyperintensity on T2-weighted images without muscle fiber tearing. Similarly, abnormalities observed on sonography but not on MRI commonly consisted of subtle increased muscle echogenicity not associated with fiber disruption. In these discordant cases, players did not have muscle fiber damage but had either edema or contusion in the injured area. In one patient, scarring from an old injury was misinterpreted on sonography as representing an acute injury but was correctly identified on MRI. This finding was confirmed during subsequent follow-up assessments with the apparent abnormality on sonography remaining unchanged. Many of the players had a history of previous hamstring injury, and residual scarring appears to be a potential cause of misdiagnosis leading to both over- and underdiagnosis of new injuries. In one patient, the field of view on the MRI was too small to include the injury. This oversight was compounded by the patient's claustrophobia and also his failure to accurately pinpoint the site of his pain.

In some cases, MRI showed irregularities in the biceps femoris muscle that appeared on sonography to be in the semitendinosus muscle. The large muscle bulk of the participants' legs resulted in each of the three hamstring muscles being composed of many muscle bundles, so it was difficult to ascertain the origin of each bundle on sonography, particularly because the biceps femoris and semitendinosus muscles have a common origin. This limitation may have caused the discrepancies. Such errors could be minimized by using the muscle insertion as a sonographic guide (biceps femoris muscle to the fibula and semitendinosus muscle at the medial tibia) rather than the origins. The use of extended fields of view should further increase the accuracy of injury localization on sonography.

Abnormalities appeared to resolve sooner on sonography than on MRI, and sonography detected fewer abnormalities than MRI at 2 and 6 weeks. The depiction of muscle injury on sonography in the acute setting is easier in the presence of extramuscular fluid collections and hematoma. However, sonography has poorer contrast resolution than MRI, and characterization of hamstring tears in the healing phases requires depiction of subtle changes in echotexture. This depiction is made more difficult with the resolution of muscle contusion and intermuscular hematoma. In this respect, it is easy to follow resolution of hyperintensity on T2-weighted images and formation of low-signal scar tissue on MRI.

In the early phases of the healing process, weak ionic bonds of immature collagen are laid down. The conversion of these weak bonds to stronger covalent bonds can take up to 6 months. The differences in the hydrogen and proton environment created during the weeks and months after an injury may further contribute to the susceptibility artifacts observed on T2-weighted images during follow-up and may also explain the decreased ability of sonography to differentiate between the subtle chemical changes that occur during healing.

Hamstring myofibrils run longitudinally within the muscle. The degree of muscle injury is proportional to the number of muscle–tendon units disrupted along the intramuscular tendon. Our study has shown that both the longitudinal length of muscle injury on MRI and the abnormal area as measured in cross section on sonography are useful predictors for the time required to return to full competition. Measurement of the longitudinal length of injury is a simple measurement as opposed to more complex calculations required to measure the cross-sectional area or estimate the volume of injured muscle. Coronal MR images centered over the tear usually depict the length of muscle tearing, although counting the number of abnormal sequential axial images is also an easy method for assessing the length of an injury. The longitudinal length of injury as identified on MRI was significantly greater than the length identified on sonography at all time points. Likewise, the cross-sectional abnormal area as measured on MRI was larger than the abnormal area identified on sonography. These differences probably reflect the superior contrast resolution afforded by MRI. On sonography, an extended field of view can be useful for this measurement and can also facilitate the detection of small increases in the amount of fluid in soft tissues.

The cross-sectional injury area viewed on sonography provided a useful prediction for time to return to competition. This latter prognostic indicator was previously reported in the MRI study of Slavotinek et al. [7]. In addition, we showed that injury to the biceps femoris is associated with increased recovery time, a finding not shown by those researchers.

It is important to note that the player's ability to return to full competition depends on many factors not assessed in our study, including player management within the club, player characteristics, medical history, and other injury characteristics. On the field, recovery may be measured by other means, such as the ability to sprint pain-free or the absence of pain and stiffness during a full training session. All these factors are included in the return-to-full-competition criterion that we established as a measure of successful rehabilitation. As such, our criteria can be viewed only as a subjective measure of successful rehabilitation. We hypothesize that we could further improve the predictive value of the MRI and sonography parameters if player management was standardized.

Our study found that the biceps femoris muscle was the most common hamstring muscle injured, confirming the findings of earlier reports [8, 9]. The intramuscular tendon was the most common site of injury, followed by tears of the epimysial covering, which are more easily identified on sonography because of their superficial location. However, sonography was not as sensitive as MRI for localizing tears along the central intramuscular tendon of the biceps femoris muscle, particularly in bulky hamstrings in which spatial resolution diminishes with depth. In these cases, sonography was more likely to identify abnormal echotexture within the muscle belly but did not reveal as well the fibril tearing from the central intramuscular tendon slip or hematoma tracking between the torn fibrils. On sonography, this tendon could be visualized only as an interface between the converging myofibrillar bundles rather than as a distinct entity. Hence, sonography was not as sensitive as MRI for localizing fibril tears along the central intramuscular tendon of the biceps femoris muscle and could only depict these tears as being localized in the muscle belly. These differences may account for the moderate agreement regarding the site of injury between the two techniques.

There was no significant difference in the time it took players with musculotendinous junction tears to return to play compared with players who had sustained a myofascial injury (25.9 vs 27.1 days). The median duration until return to play for the entire study population was 21 days (range, 4–56 days), which includes those players in whom imaging studies were found to show normal findings. When evaluated as a separate group, these players had a significantly faster return to competition (median, 7 days; range, 7–14 days; $p < 0.001$). The fact that these players seem to recover and return to play relatively quickly suggests an alternative diagnosis, such as a back-related problem or localized spasm of the muscle.

The presence of either focal collections of linear hyperintensity as hypoechoic fluid tracking between muscles was noted on T2-weighted images in just over half of the patients (32/60). This finding is probably the consequence of intramuscular hemorrhage and fluid pooling within the muscle and, in some cases, extending through an epimysial tear to the extramuscular surface. Intramuscular hemorrhage and fluid pooling sometimes track to the skin surface where these injuries manifest as skin bruising. We did not find a significant correlation between the presence of intramuscular fluid collection and the length of the convalescent period.

Athletes typically become symptom-free within 10 days after an injury, although histopathologically the healing process takes weeks to months to complete [15–17]. Interestingly, some players showed larger injuries 2 weeks after their acute assessment. These injuries were evident on both MRI and sonography and may be due to insufficient rehabilitation and premature return to training. During the competition season, athletes often return to competition before the healing process is completed. This phenomenon is underscored by the rapid decline of pain and stiffness associated with the injury, leaving the player with the impression that healing is complete. Among those players in our study who presented with radiologic abnormalities at the baseline assessment, 15 (35.7%) of 42 players on MRI and 10 (23.8%) of 42 players on sonography still had residual abnormal imaging findings at 6 weeks. However, all but one player were symptom-free and had returned to competition. These findings confirm that it takes time for imaging results to return to normal, and this lag probably reflects the process of healing and repair and may further explain the high reinjury rate of over 30% among professional football players in Australia [5, 6, 14, 18]. Despite this, many athletes return successfully to play without adverse sequelae, at least in the short term.

Our study population was limited to elite young athletic men and may therefore not reflect the injury characteristics of a more general patient population. However, our results comparing sonography and MRI in the acute setting and during healing remain valid for hamstring injuries regardless of the type of patient population. Complete tears of the hamstring muscles commonly described as grade 3 tears that require surgical intervention were not included in this study. One shortcoming of our study was the reluctance of some professional athletes to return for the 2- and 6-week assessments. We had some difficulty convincing professional athletes who were largely symptom-free to return for repeated imaging. More important was the lack of pathologic gold standard to compare with our MRI and sonographic observations. Both MRI and sonographic interpretations were made in consensus, and we have no measure of either inter- or intraobserver variation. Our study is limited in that all players were recruited from the Australian Football League and play a game characterized by sprinting and leaping found only in Australia. However, we believe our findings may potentially be extrapolated to other types of football and sports.

In conclusion, the results of our study show that sonography and MRI are both sensitive and effective in the assessment of hamstring injuries. In the acute setting, sonography is as sensitive as MRI and provides a cost-effective imaging technique for most hamstring injury presentations among professional athletes and potentially also for members of the general community. However, for elite athletes concerned with optimizing rehabilitation, as well as those requiring follow-up imaging, MRI appears to be the technique of choice. Certain radiologic criteria are useful in predicting rehabilitation of the hamstring muscle complex and in the future may assist in more accurate management of professional athletes.

Acknowledgments

We thank the Australian Football League and MIA Group Victoria for financial assistance; Price Warren for his contribution to this article; and all the players and the medical and technical staff who participated in this study.

References

1. Garrett WE, Rich FR, Nikolasu PK, Vagler JB III. Computed tomography of hamstring muscle strains. *Med Sci Sports Exerc* 1989;21:506–514
2. Sallay PI, Friedman RL, Coogan PG, Garrett WE. Hamstring muscle injuries among water skiers: functional outcome and prevention. *Am J Sports Med* 1996;2:1300–1306
3. Heiser TM, Weber J, Sullivan G, Clare P, Jacobs RR. Prophylaxis and management of hamstring injuries in intercollegiate football players. *Am J Sports Med* 1984;5:368–376
4. Pomeranz SJ, Heidt RS. MR imaging in the prognostication of hamstring injury. *Radiology* 1993;189:897–900
5. Verrall GM, Slavotinek JP, Barnes PG, Fon GT, Spriggins AJ. Clinical risk factors for hamstring muscle strain injury: a prospective study with correlation of injury by magnetic resonance imaging. *Br J Sports Med* 2001;35:435–440
6. Orchard JW. Intrinsic and extrinsic risk factors for muscle strains in Australian football. *Am J Sports Med* 2001;29:300–303
7. Slavotinek JP, Verrall GM, Fon GT. Hamstring injury in athletes: using MR imaging measurements to compare extent of muscle injury with amount of time lost from competition. *AJR* 2002;179:1621–1628
8. Brandser EA, El-Khoury GY, Kathol MH, Callaghan JJ, Tearse DS. Hamstring injuries: radiographic, conventional tomographic, CT and MR imaging characteristics. *Radiology* 1995;197:257–262
9. De Smet AA, Best TM. MR Imaging of the distribution and location of acute hamstring injuries in athletes. *AJR* 2000174:393–399
10. Speer KP, Lohnes J, Garrett WE. Radiographic imaging of muscle strain injury. *Am J Sports Med* 1993;1:89–95
11. Koulouris G, Connell D. Evaluation of the hamstring muscle complex following acute injury. *Skeletal Radiol* 2003;32:582–589
12. Koulouris G, Connell DA. The hamstring muscle complex: an imaging review. *Skeletal Radiology* (in press)
13. Fleiss JL. Measuring nominal scale agreement among many raters. *Psychol Bull* 1971;76:378–382
14. Orchard J, Seward H. Epidemiology of injuries in the Australian Football League, seasons 1997-2000. *Br J Sports Med* 2002;36:39–44
15. Zarins B, Ciulb JV. Acute muscle and tendon injuries in athletes. *Clin Sports Med* 1983;2:167–182
16. Stauber WT. Eccentric action of muscles: physiology, injury and adaptation. *Exerc Sports Sci Rev* 1989;17:157–185
17. Garrett WE. Muscle strain injuries. *Am J Sport Med* 1996;24:52–58
18. Orchard JW, Marsden J, Lord S, Garlick D. Preseason hamstring muscle weakness associated with hamstring muscle injury in Australian footballers. *Am J Sports Med* 1997;25:81–86